AIR FORCE MATERIALS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND

CONTRACT AF 33(615)-2480
PROJECT 7381; TASK 738103

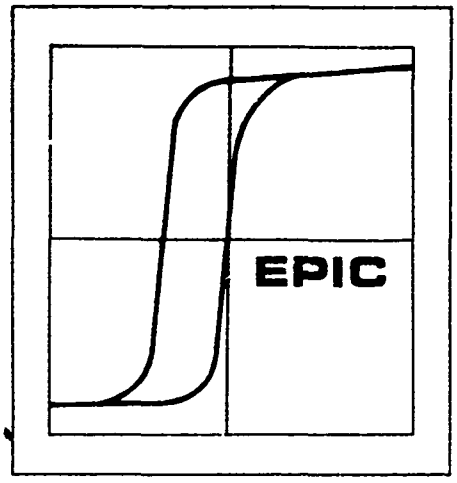
SILICON CARBIDE

Data Sheets

M. Neuberger

DS-145

June 1965



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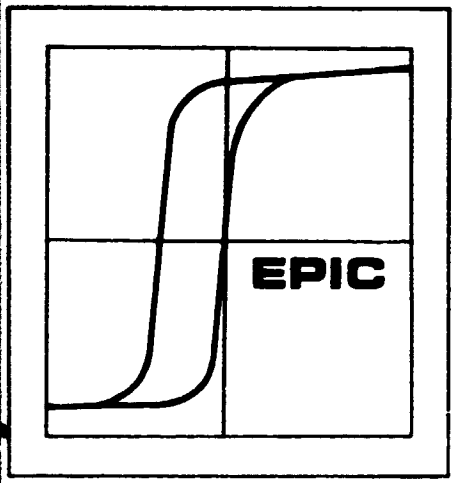

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FOREWORD

This report was prepared by Hughes Aircraft Company under Contract No. AF 33 (615)-2460. The contract was initiated under Project No. 7381, Task No. 738103. The work was administered under the direction of the Air Force Materials Laboratory, Research and Technology Division, with Mr. R. F. Klinger acting as Project Engineer.

The Electronic Properties Information Center has been established to collect, index and abstract the literature on the electrical and electronic properties of materials and to evaluate and compile the experimental data from that literature. A modified coordinate index to the literature is machine-stored and printed for manual use. The Center published summary reports, thesauri, glossaries, data sheets and similar publications as sufficient information is evaluated and compiled. This report consists of the compiled data sheets on Silicon Carbide.

Many persons have contributed to the program which this report represents. The author wishes especially to acknowledge the contributions of the following: John W. Atwood, C.L.M. Blocher, D. Gough, D.L. Grigsby, D.H. Johnson, H. Thayne Johnson, Thomas J. Lyndon, J.T. Milek, Emil Schafer and C.A. Schill.

Special thanks are extended to Dr. J. J. Grossman for his efforts in reviewing all technical data prior to publication.

ABSTRACT

These data sheets present a compilation of a wide range of electrical, optical and energy values for alpha and beta-silicon carbide in bulk and film form. Electrical properties include conductivity, resistivity, dielectric constant, Hall coefficient, mobility, lifetime and thermoelectric effects. Emission data have been broken down into the varied electron and photon emissions which result from application of energy in the electromagnetic spectrum. Energy data include energy bands, energy gap and energy levels for variously-doped silicon carbide, as well as effective mass tables, work function, and cross sections. The optical properties include absorption, reflection and refractive index. Other magnetic data and irradiation effects are included, as well as several bordering physical phenomena, such as piezoelectric properties, Debye temperature and thermal conductivity. Each property is compiled over the widest possible range of parameters from references obtained in a thorough literature search.

A crystallographic summary has been added.

This report has been reviewed and is approved for publication.

H. Thayne Johnson, Head
Electronic Properties Information Center

for John W. Atwood
Project Manager

TABLE OF CONTENTS

INTRODUCTION

In June 1961, a program was initiated under the direction of the Air Force to collect, index and abstract the literature on the electrical and electronic properties of materials and to evaluate and compile the experimental data from that literature. Placed at Hughes Aircraft Company in Culver City, California, the program, now called the Electronic Properties Information Center, was originally intended to cover ten major categories of materials: Semiconductors, Insulators, Ceramics, Ferroelectrics, Metals, Ferrites, Ferromagnetics, Electroluminescent Materials, Thermionic Emitters, and Superconductors.

During the first year, studies were completed on the Semiconductor and Insulator categories; and Ceramics was discontinued as a separate category and subsumed under the other nine. Vocabulary studies have now been completed on all categories, and retrospective documentation is virtually complete for Semiconductors and Insulators. A full index to the literature is maintained, and publications such as data sheets, summary reviews, glossaries, and thesauri are issued periodically. The use of the Center and these publications are available to anyone wishing information within the scope of the Center's objectives. A full list of publications to date appears at the end of this report.

The first step in the preparation of data sheets is the retrieval, by manual modified coordinate index, of all literature on the material to be compiled. Bibliographies are checked to ensure the inclusion of all relevant literature and the assembled articles are given to the specialist doing the evaluation and compilation.

Evaluation is confined to primary source data except when only secondary citations are available. If equally valid data are available from several

sources, all are given. Data are rejected when judged questionable because of faulty or dubious measurements, unknown sample composition, or if more reliable data are available from another source. Selection of data is based upon that which is judged most representative, precise, reliable and which covers the widest range of variables.

Pure silicon carbide is colourless, with a Mohs hardness over 9, almost equal to that of the diamonds that Acheson was attempting to synthesize when he created silicon carbide artifically in the arc furnace in 1891. The natural material, Moissanite, was discovered as small hexagonal plates in meteoric iron about 15 years later in 1904. Commercial silicon carbide is black, with a bluish or greenish iridescence, it is refractory to heat up to 1000°C, unreactive to chemical attack and melts at 2830°C. It is now produced in large quantities by the electric furnace method at Niagara Falls, and is used extensively as an abrasive, for drills and highly refractory bricks. In 1963, its capability as a CW diode laser was disclosed, [Ref. 17972].

A silicon carbide p-n junction operating at room temperature has an emission peak at 4560Å with a linewidth of less than 5Å, at threshold current densities of 120 amps/cm^2. This important discovery has renewed interest in the material. It is however, an extremely difficult and refractory material to handle and this fact is reflected in the quantity of published material. One hundred and eighty four papers in all, were available to represent work done since about 1955. The older data are well covered in Gmelins Handbuch, and it is only the new techniques of the past ten years that have made possible samples of predetermined quality. Of the one hundred and eighty four papers, seventy nine were used in these data sheets.

Within every property section, we have tried to include every possible parameter and range of experimental condition tested. All the available information on test and sample specifications is also given. All graphs and tabular data are extracted from the article and quoted without alteration of any kind.

In previous compilations, materials have been arranged to show firstly data on pure samples, and then by the various dopants. Silicon carbide however, has thus far, not been produced pure from the standpoint of either dopants or crystal type. This question will be discussed more fully in the section on crystallography. In any event, the arrangement is practically self-explanatory, the data being divided into the alpha and beta forms, single crystal and films, and the nitrogen-doped (n-type) or the aluminum-doped (p-type).

In tabular data, values are variously arranged. In some cases it is by dopant, in others by numerical value. On occasion, however, the values from one reference may be kept together for simple comparison.

The references, from which the data are drawn, are shown by reference numbers below each graph with the full bibliographic information at the end of the data sheets. The bibliography is referred to and listed in the order of entry into the Center (accession number). This provides a quick cross reference into the index used with the literature.

CRYSTALLOGRAPHY

Silicon carbide is an unique material and a précis of its crystallographic characteristics is thoroughly covered by Gmelins Handbuch.[1] It is of the utmost importance to note, however, that the energy gap value changes with crystal structure by 1 ev; from 2.2 ev for the beta-silicon carbide to 3.12 ev for the alpha-silicon carbide (6H).[2] Such details, germane to the electronic properties of silicon carbide are given here.

Silicon carbide is both polymorphic and polytypic. The beta form is cubic and also called the low-temperature form. The alpha form is hexagonal and has 37 types of which 14 are hexagonal and 23 are rhombohedral. Many of these types are structurally equivalent in two directions with the same dimensions and lattice arrangement but dissimilar in the c-direction. Nomenclature is given according to Ramsdell, the chief investigator in this field, by H for hexagonal or R for rhombohedral. The number indicates the total number of silicon carbide layers in the (0001) direction which repeats one each of the unit crystal cells.

The three most generally occurring types are the 6H, often called (II modification), the 4H (III modification), both dihexagonal-dipyramidal and the 15R, rhombohedral, ditrigonal-pyramidal.[1] These occur together in varying percentages as a result of variations in growth conditions. These include changes in temperature, pressure, impurities present in the charge or excess of either silicon or carbon. Nitrogen is the major impurity and therefore pure material must be synthesized in an ambient inert gas (argon is used). Doping, with nitrogen, aluminum, boron or phosphorus is controlled. Twinning is common; there are three kinds, all on the basal plane and on three edges.

The beta form is body-centered cubic and very dense. Its yellow color is not due to any impurity, but to a shift of the fundamental absorption edge into the visible at ∿ 4400 Å. Following are the four best lattice constant values:

a_o (kX)	
4.350	- very pure powder
4.352	- colourless crystal
4.349	- powder
4.348	- crystal [1]

The alpha form has a tetrahedral lattice with silicon in the center and carbon at the four corners like silicon dioxide.

6H a_o(kX)	c_o(kX)	4H a_o(kX)	c_o(kX)	
3.075	15.088	3.0739	10.061	
3.073	15.068	3.076	10.046	
3.073	15.079	3.073	10.053	
3.076	15.070	3.08	10.09	
3.08	15.17	3.09	10.09	
3.09	15.17			[1]

15R H	a_o(kX)	R	a_o(kX)	α	
	3.076		12.78	13°55'	
	3.073		12.703	13°54'	
	3.073		12.691	13°54.5'	
	3.09		12.78	13°55'	
	3.08		12.775	13°52'	[1]

Ramsdell[3] in 1952 reported five hexagonal modifications including 8H, with an eight layer hexagonal unit cell,

a_o = 3.073 kX $\qquad$ c_o = 20.106 kX

In 1953[4] he reported 19H with a structure showing the zigzag sequence 22232323,

a_o = 3.073 $\qquad$ c_o = 47.75 kX.

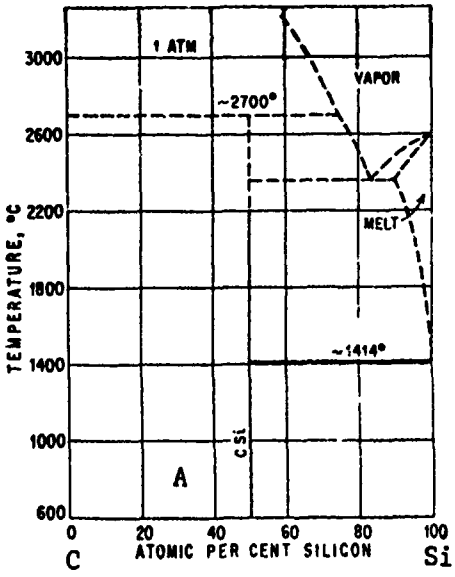
In 1964 Chang-Lin Kuo[5] described two new polytypes:

417R, a_o = 3.0806Å $\qquad$ c_o = 1050.7Å

453R, a_o = 3.0806Å $\qquad$ c_o = 1141.4Å

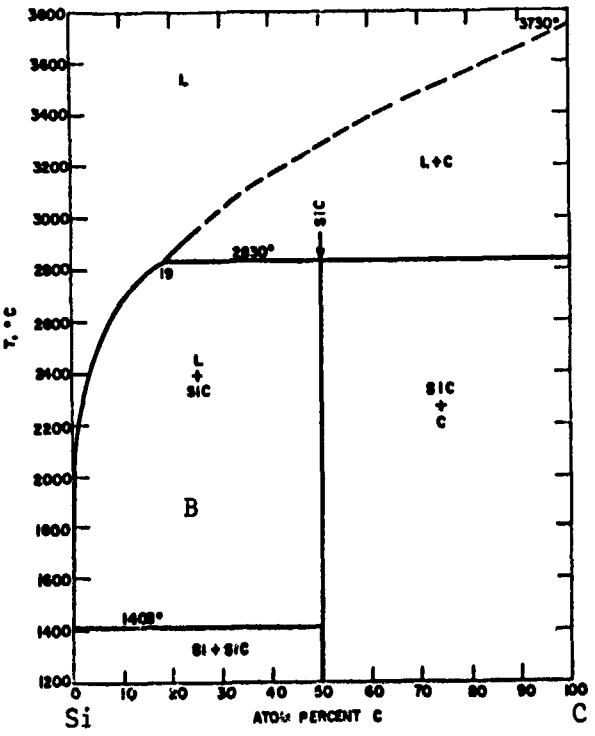
These last references indicate the complexity and the continued interest in the crystallography of silicon carbide.

The commercial material ranges in color from yellow thru green and blue to black. Silicon carbide is uniaxial positive and pleochroic.[6]



The phase diagram A is drawn from four points taken at 1 atm. pressure.[7]

B is a more recent phase diagram drawn from a large number of points at 35 atmos. pressure in argon over a range of 1408°C to 2900°C.[8]



Transformation from the beta to the alpha form is apparently by the vapour phase and not the solid, even at temperatures up to the melting point. The beta form is grown below 2000°C from the vapour and forms plates.[9] Silicon carbide crystals are not piezoelectric.

1 GMELINS HANDBUCH DER ANORGANISCHEN CHEMIE; achte völlig neu bearbeitete Auflage. Silicium. Teil B. Weinheim, Verlag Chemie, GMBH, 1959.

2 KNIPPENBERG, W.F. Growth Phenomena in Silicon Carbide. PHILIPS RES. REPTS., v. 18, no. 3, June 1963. p. 161-274. [Acces. no. 17402]

3 RAMSDELL, L.S. and J.A. KOHN. Developments in Silicon Carbide Research. ACTA CRYST., v. 5, 1952. p. 215-224.

4 RAMSDELL, L.S. and R.S. MITCHELL. A New Hexagonal Polymorph of Silicon Carbide, 19H. AMERICAN MINERALOGIST, v. 38, 1953. p. 56-59.

5 CHANG-LIN KUO. Two New Polytypes of Silicon Carbide 417R and 453R. WU LI HSUEH PAO, v. 20, 1964. p. 444-446.

6 DANA, J.D. The System of Mineralogy of James Dwight Dana and Edward Salisbury Dana. Yale University, 1837-1892. v.1, 7th ed. Entirely rewritten and greatly enlarged by PALACHE, C., et al. N.Y., Wiley, 1944. p. 123.

7 NOWOTNY, H., et al. MONATSH CHEM., v. 85, 1954, p. 255-272 as cited in CONSTITUTION OF BINARY ALLOYS, by HANSEN, M., N.Y., Mc Graw-Hill, 1958.

8 SCACE, R.I. and G.A. SLACK. The Silicon Carbide and Germanium Carbide Phase Diagrams. In: CONF. ON SILICON CARBIDE, BOSTON, 1959. SILICON CARBIDE, A HIGH TEMPERATURE SEMICONDUCTOR, PROC., ed. by O'CONNOR, J.R. and J. SMILTENS. N.Y., Symposium Pub. Div., Pergamon Press, 1960. p. 366-371. [Acc. no. 17418]

9 GORIN, S.N. and A.A. PLETYUSHKIN. Structural Characteristics of Cubic Silicon Carbide Crystals Grown from the Vapor Phase. IZV. AKAD. NAUK SSSR., SER. FIZ., v. 28, 1964. p. 1310-1315.

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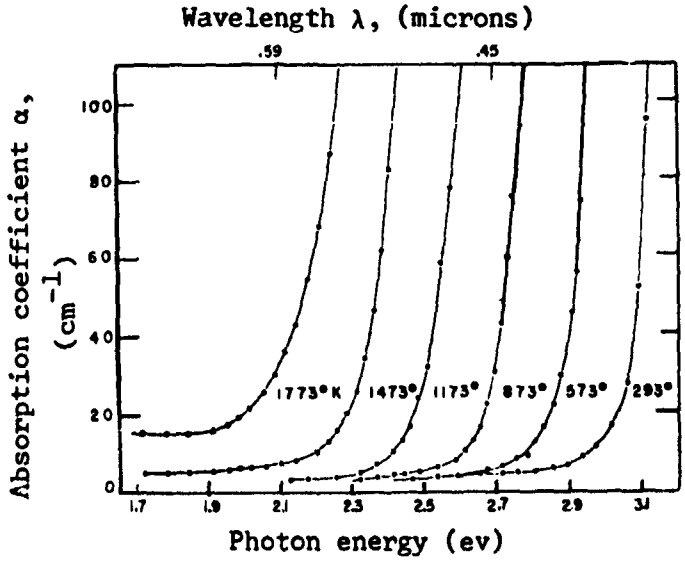
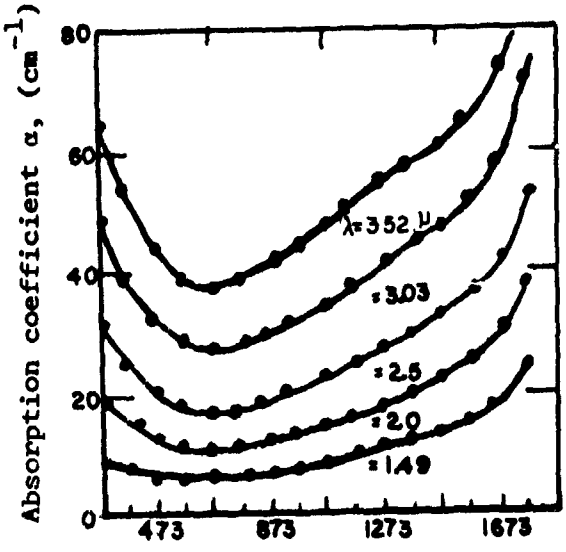
SILICON CARBIDE

ABSORPTION

Absorption as a function of wavelength for pure, colourless, single crystal, alpha-silicon carbide (6H), at several temperatures.

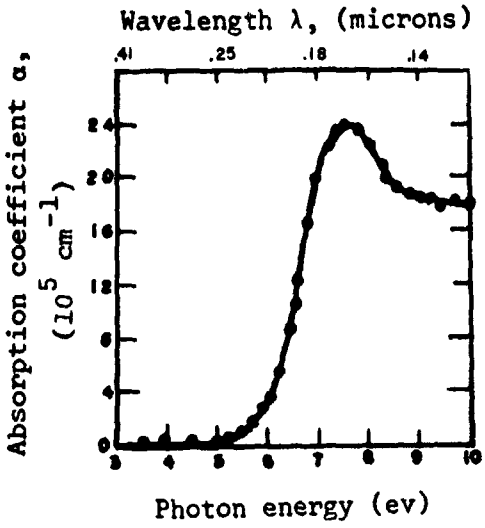


[Ref. 4434]



Absorption as a function of temperature for pure, colourless, single crystal alpha-silicon carbide (6H), at several wavelengths.

[Ref. 4434]

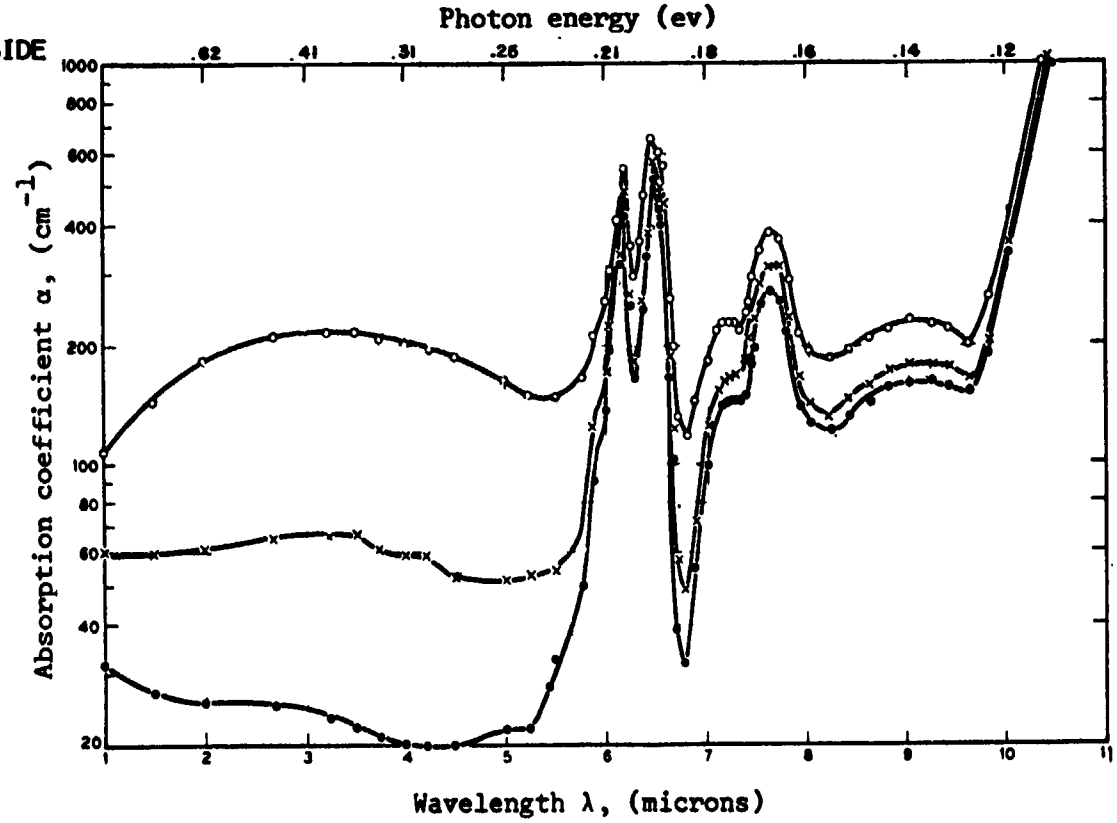


Intrinsic absorption as a function of wavelength at 300°K, for single crystal, alpha-silicon carbide (6H), cut parallel to c-axis. Above 5 ev points are calculated from reflectivity data.

[Ref. 17419]

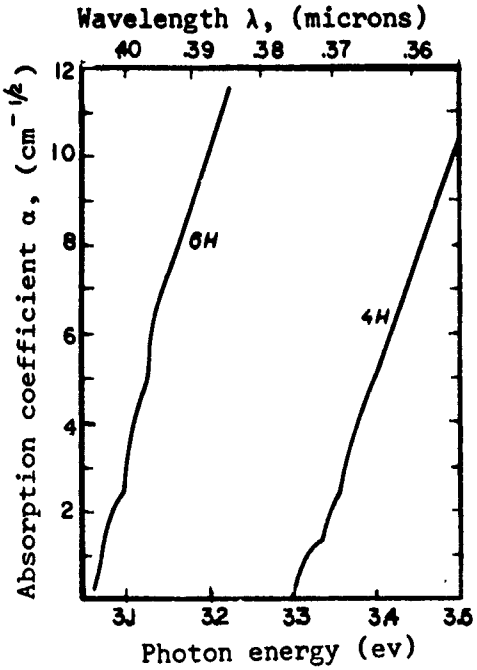
SILICON CARBIDE

ABSORPTION



Absorption as a function of wavelength for single crystal, n-type, alpha-silicon carbide, (6H). Curves calculated from transmission data, at 300°K. An N-doped inhomogeneous green crystal is used, $\rho \sim 1$ ohm-cm. The 3 curves indicate varying carrier concentrations.

[Ref. 628]



Absorption as a function of wavelength for single crystal, alpha-silicon carbide at 77°K, $E \perp$ c-axis.

The two curves indicate the absorption edge difference between the (6H) and (4H) polytype.

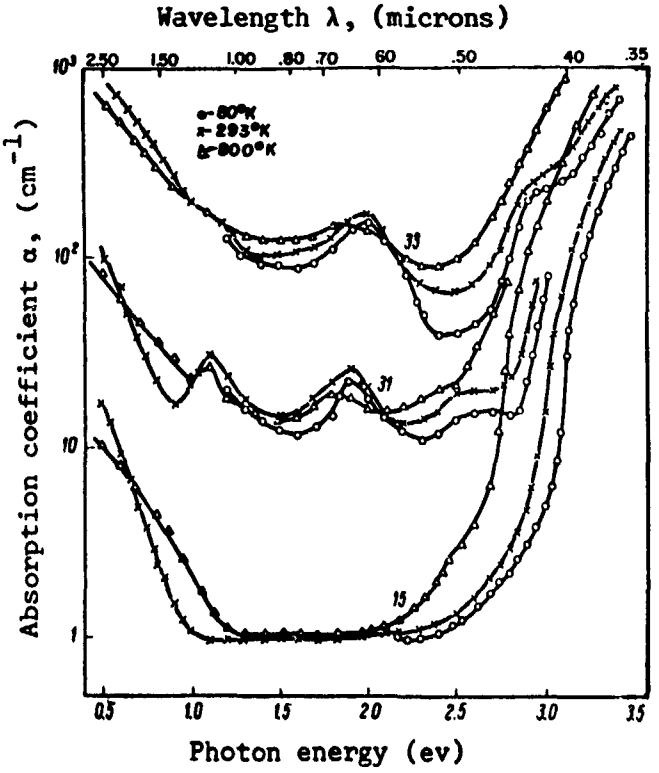
[Ref. 8792]

SILICON CARBIDE

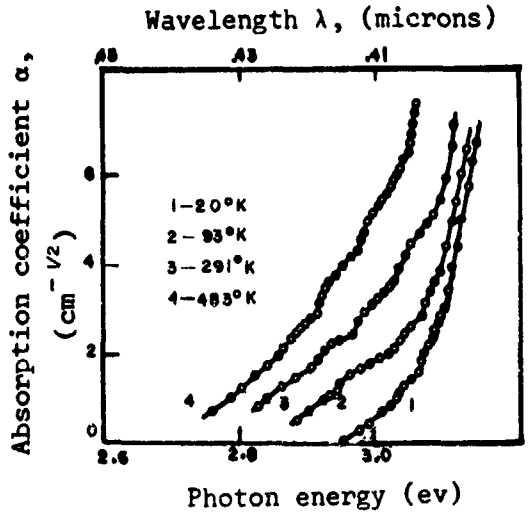
ABSORPTION

Absorption as a function of wavelength for single crystal, n-type, alpha-silicon carbide, nitrogen-doped.

carrier concentration	ρ (ohm-cm)
15 - 4.5 x 10^{17}/cc	0.2
31 - 40 x 10^{17}	0.48
33 - 200 x 10^{17}	0.0085



[Ref. 16397]



Absorption as a function of wavelength for single crystal, alpha-silicon carbide, (6H), at four temperatures.

[Ref. 13404]

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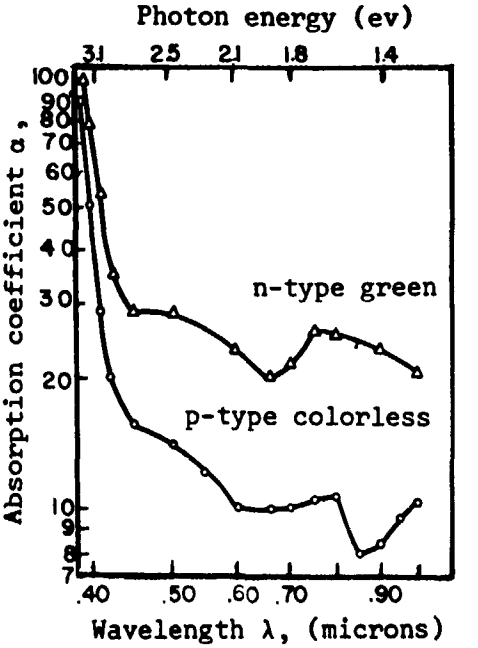
SILICON CARBIDE

ABSORPTION

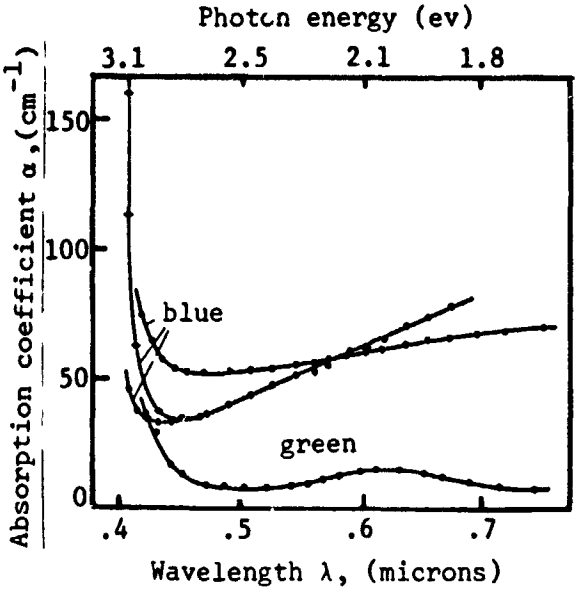
Absorption as a function of wavelength for single crystal, alpha silicon carbide at 300°K.

p-type colorless, $\rho = 10^4$ ohm-cm, $n \sim 10^{14}$/cc.

n-type green, $\rho = 10^2$ ohm-cm.



[Ref. 2863]



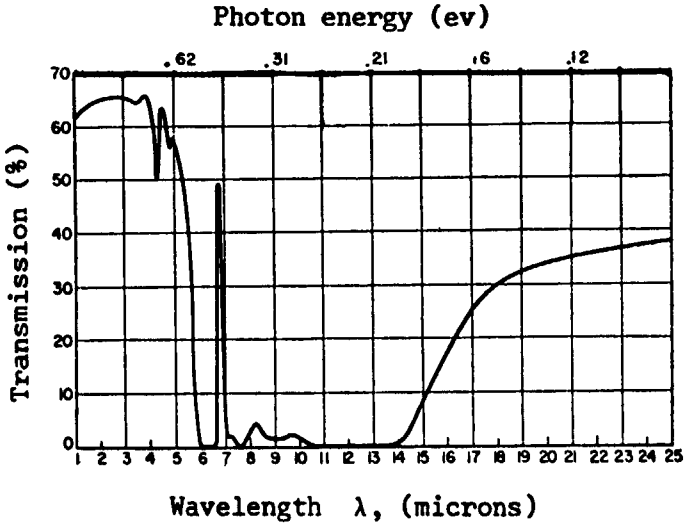
Absorption as a function of wavelength for single crystal alpha silicon carbide, (6H), at 300°K. Blue crystals are p-type, aluminum-doped, $\rho = 50$ ohm-cm, green is n-type, $\rho = 3$ ohm-cm.

[Ref. 2514]

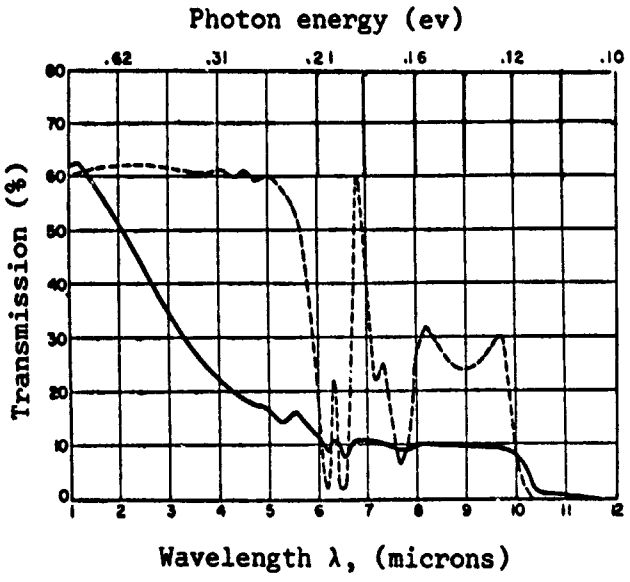
SILICON CARBIDE

ABSORPTION

Infra-red transmission of clear, single crystal, n-type, alpha silicon carbide, (6H), at 300°K.



[Ref. 17415]



Infra-red transmission of clear and light green, nitrogen-doped, single crystal, n-type, alpha silicon carbide, (6H), at 300°K.

---- clear, 0.07 mm thick

—— green, 0.007 mm thick.

[Ref. 17415]

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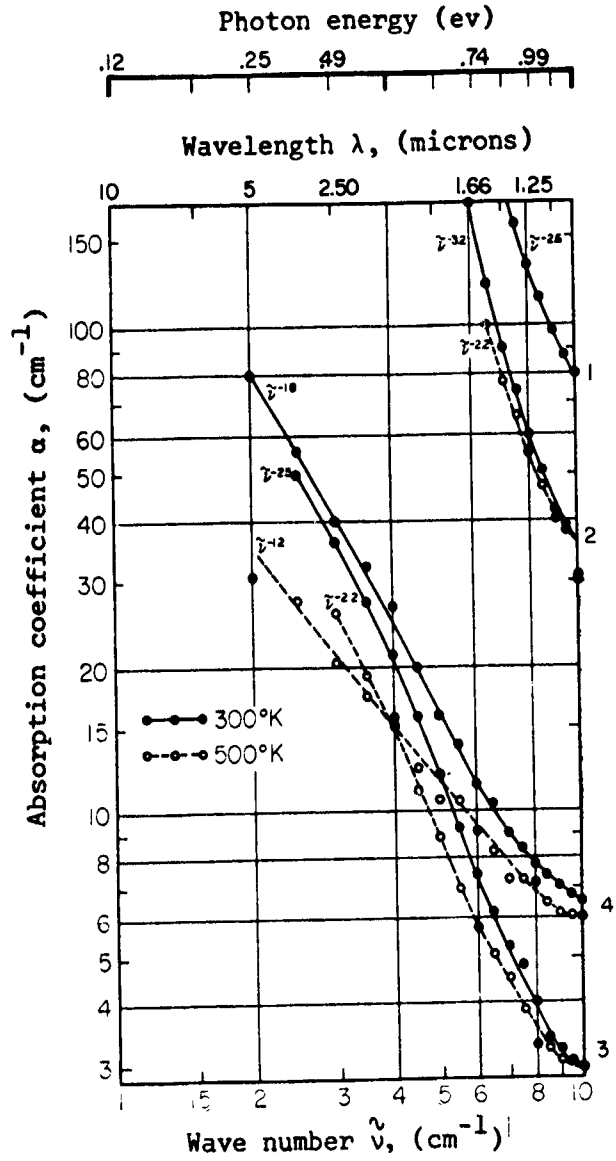
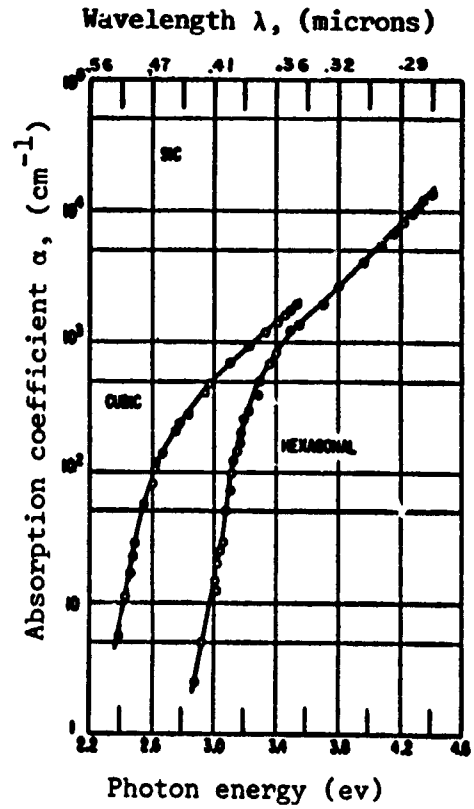
SILICON CARBIDE

ABSORPTION

Absorption as a function of wavelength for single crystal, alpha and beta-silicon carbide, at 300°K. The alpha form is (6H), polytype.





[Ref. 787]

Absorption as a function of wavelength for single crystal, n-type, silicon carbide. 1, 2, and 3 are alpha-form, commercial grade.

1 - n = 6.7×10^{18}/cc
2 - n = 2.5×10^{18}
3 - n = 9.5×10^{16}

4 is pure beta-form, n = 1.3×10^{17}/cc.

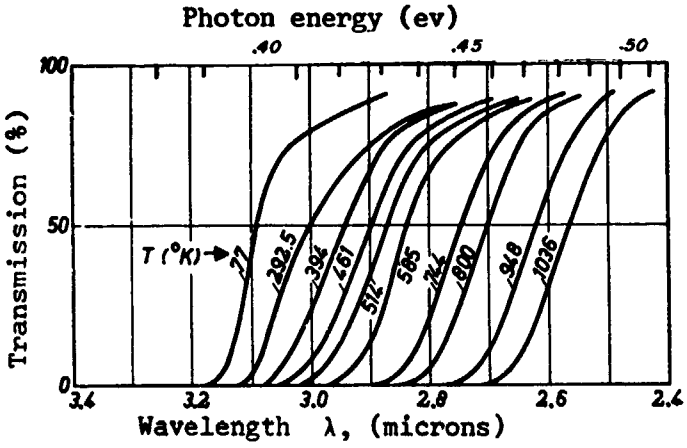
The wave number power on the curves shows the absorption slope.

[Ref. 17233]

SILICON CARBIDE

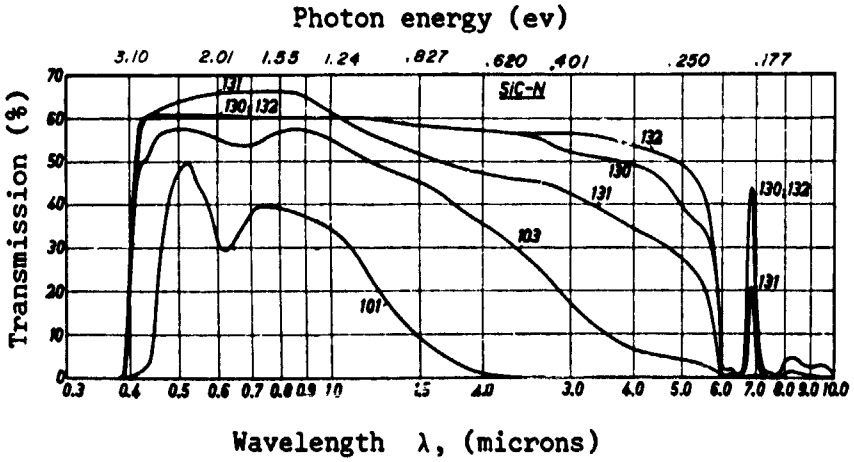
ABSORPTION

Transmission as a function of wavelength for single crystal, n-type, alpha-silicon carbide at various temperatures.



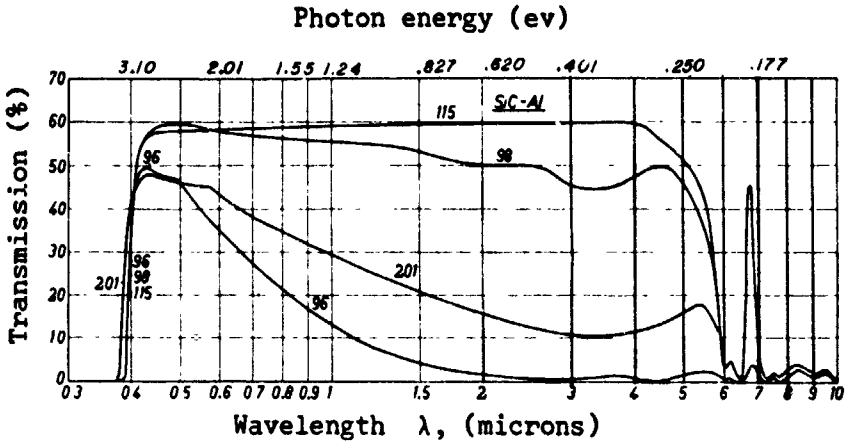
[Ref. 3607]

Transmission as a function of wavelength for single crystal, n-type, alpha-silicon carbide at 300°K. 132 is pure, argon grown. The other samples show increasing amounts of the nitrogen dopant.



[Ref. 3607]

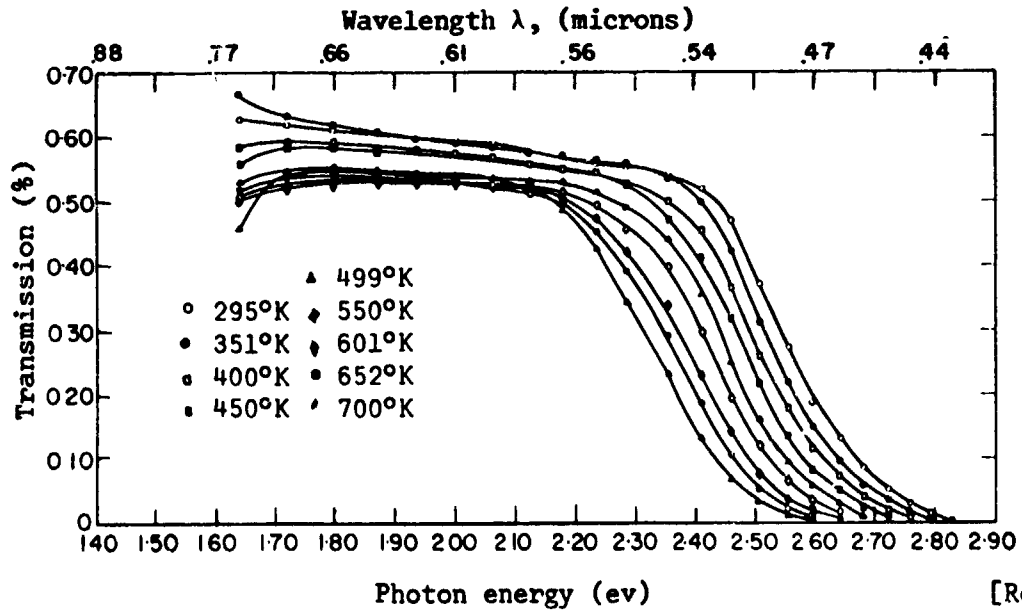
Transmission as a function of wavelength for single crystal, p-type, alpha-silicon carbide at 300°K. 115 is pure, argon grown, 98, 201, and 96 show increasing amounts of the aluminum dopant.



[Ref. 3607]

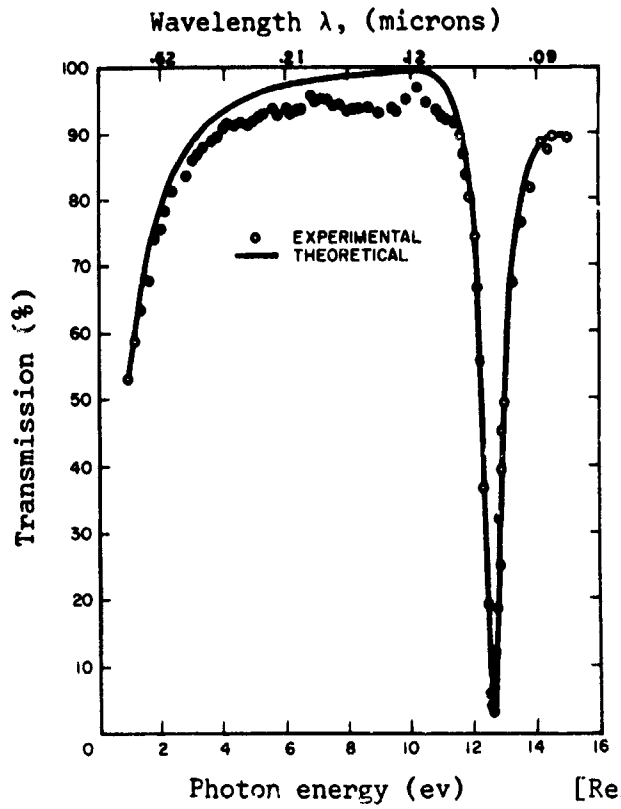
SILICON CARBIDE

ABSORPTION



[Ref. 18056]

Transmission as a function of wavelength for single crystal, n-type, beta-silicon carbide at temperatures from 295-700°K. $n \sim 10^{17}$/cc, $\rho_{500K} \sim 0.1$ ohm-cm.



[Ref. 627]

Transmission as a function of wavelength for polycrystalline beta-silicon carbide film at 300°K.

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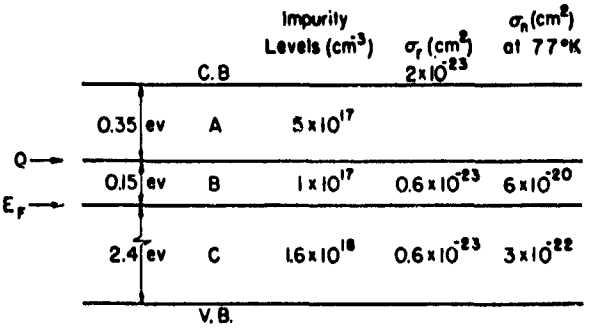
SILICON CARBIDE

CROSS SECTIONS

Symbol	Value	Sample	Test Method	Temperature	Ref.
σ	$\sim 10^{-23}$ cm^2	Al-doped, single crystal, α-silicon carbide p-n junction	electroluminescence	300°K	368

calculated for intrinsic recombination



Impurity level densities, and recombination cross-sections for both radiative and non-radiative transitions at 77°K. derived from a study of the electroluminescence of single crystal, alpha-silicon carbide p-n junctions between 77-830°K, 0.04 to 2.5 microns and 100 microamps/cm^2 to 3 amps/cm^2.

Q - the Quasi-Fermi level
E_F - the Fermi level
σ_r - average cross-section for hole-electron radiative recombination
σ_n - average cross-section for hole-electron non-radiative recombination

[Ref. 368]

SILICON CARBIDE

DEBYE TEMPERATURE θ

Value	Sample	Test Method	Temperature	Ref.
1200°K	high purity, single crystal	calc. from thermal conductivity meas.	>300°K	17406
913°K		calc. from specific heat measurement	53-73°K	*Gmelin
949°K			73.5°K	
1192°K			700-900°K	

* GMELINS HANDBUCH DER ANORGANISCHEN CHEMIE; achte völlig neu bearbeite Auflage. Silicium. Teil B. Weinheim, Verlag Chemie, GMBH, 1959. p. 820.

SILICON CARBIDE

DIELECTRIC CONSTANT

Symbol	Value		Sample	Test Method	Temperature	Ref.
ε_o	10.62	27**	single crystal, pure	1 kc	20°K	3410
	10.38	17		5		
	10.26	5		32		
	10.23	3		100		
	10.99	49		1	77°K	
	10.69	29		5		
	10.42	14		32		
	10.34	8		100		3410
ε_o	10.0 ± 0.1		single crystal, α, ρ > 1 ohm-cm	IR optical, 1-25μ, λ > 12.6μ	300°K	628
ε_∞	6.7			λ < 12.6μ		628
ε_∞	6.7		epitaxial single crystal film	IR optical measurement at 1-15μ		627
	50-200		powder	up to 30 kc		*Gmelin

** This column shows tan δ x 10^{-3} values for the sample under the given conditions.

*GMELINS HANDBUCH DER ANORGANISCHEN CHEMIE; achte völlig neu bearbeitete Auflage. Silicium. Teil B. Weinheim, Verlag Chemie, GMBH, 1959. p. 829.

SILICON CARBIDE

EFFECTIVE MASS

Symbol	Value	Sample	Test Method	Temperature	Ref.
m^*	2.5 (calc.)	single crystal, p-, n-type, $n = 8 \times 10^{19}$/cc	elec. conductivity and Hall measurement		2419
m_n	0.6	single crystal, n-, and p-type	"	300°K	3608
m_p	1.2-2	single crystal, α, N-, B- or Al-doped	"	"	3608
m_p^*	∿1.0	single crystal, p-type, α,	mobility meas. from Hall cond. data	77-1500°K	8783
m_n	0.72	Al- and B-doped			
m_p	3.5				8783

* - density of states Effective Mass

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SILICON CARBIDE

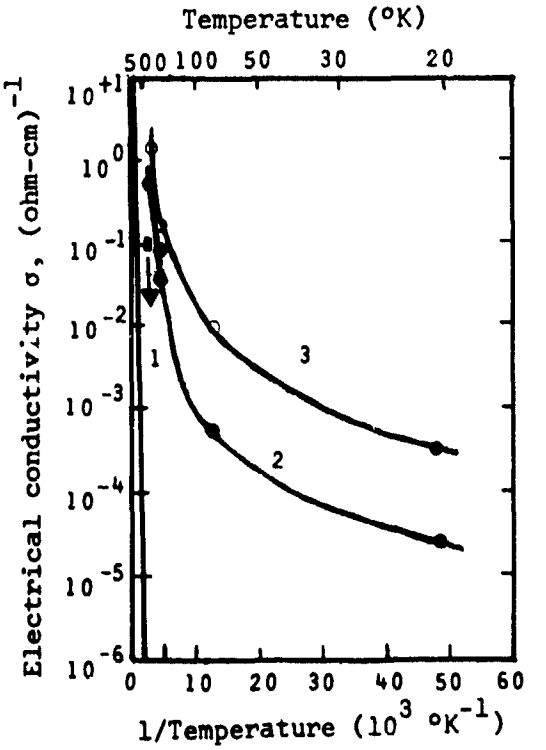
ELECTRICAL CONDUCTIVITY

Electrical conductivity as a function of temperature for single crystal, alpha-silicon carbide.

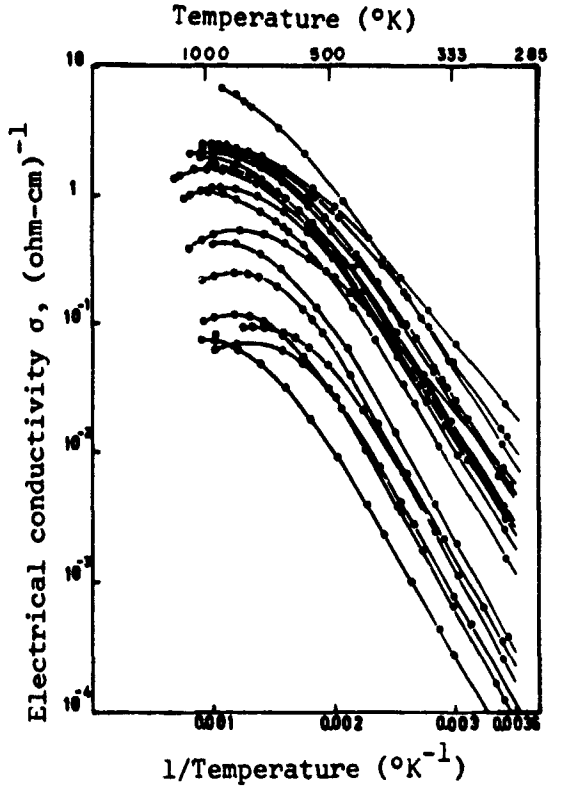
1 - n-type, N-doped, $n \sim 10^{17}$/cc., (6H)

2 - n-type, N-doped, $n \sim 10^{19}$/cc., (6H)

3 - n-type, Al-doped, $n = 4 \times 10^{19}$/cc., (6H) and (15R).



[Ref. 17725]



Electrical conductivity as a function of temperature for p-type, single crystal, alpha-silicon carbide.

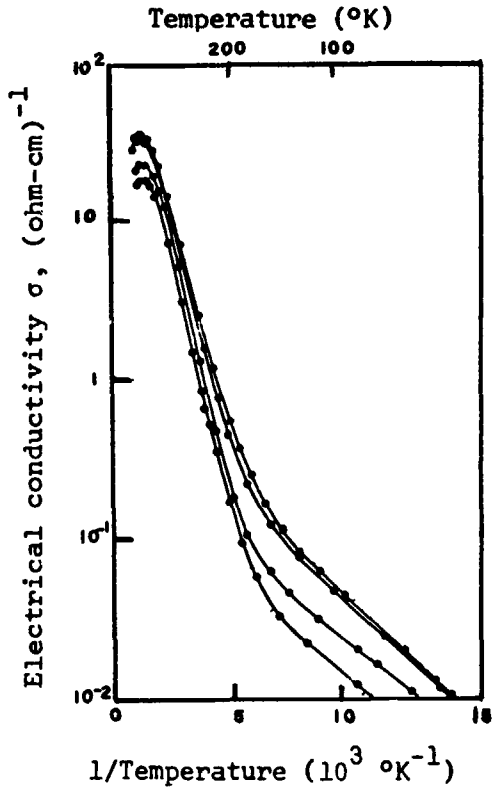
$n = 2 \times 10^{17}$ to $> 10^{20}$/cc.

[Ref. 18406]

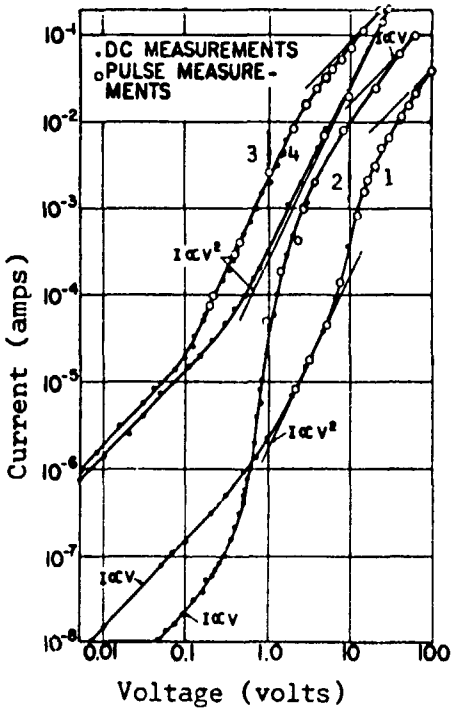
SILICON CARBIDE

ELECTRICAL CONDUCTIVITY

Electrical conductivity as a function of temperature for single crystal, alpha-silicon carbide, black crystals, with varied cross-section and carrier concentration.



[Ref. 6080]



Current voltage curves of single crystal, alpha-silicon carbide at 300°K.

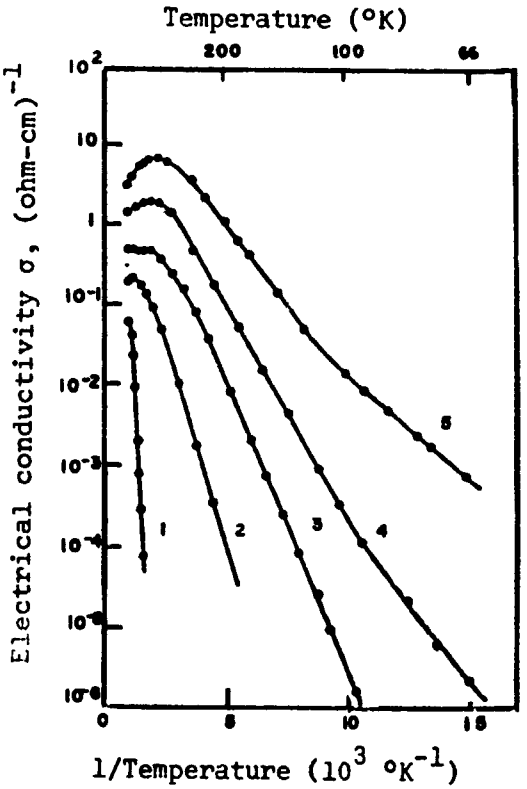
		ρ ohm-cm
1 - p-type,	B-doped,	670,000
2 - "	"	53,000
3 - "	"	11,000
4 - "	undoped	5,300

[Ref. 5908]

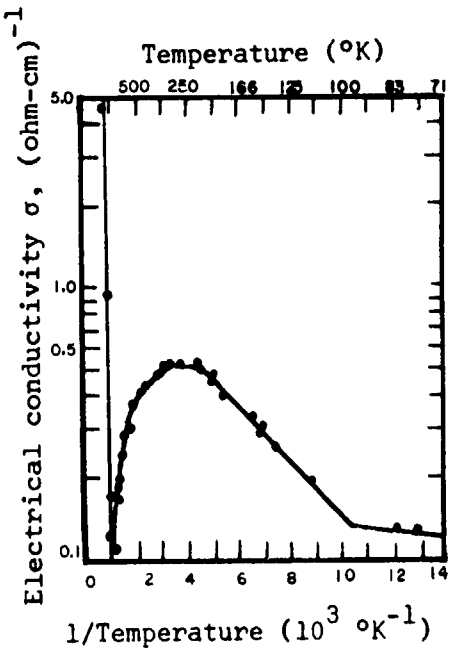
SILICON CARBIDE

ELECTRICAL CONDUCTIVITY

Electrical conductivity as a function of temperature for single crystal, alpha and beta-silicon carbide, pale yellow to green. Samples from 1 to 5 have varied cross-section and show increase in impurity by colour change from pale yellow to dark green.



[Ref. 6080]

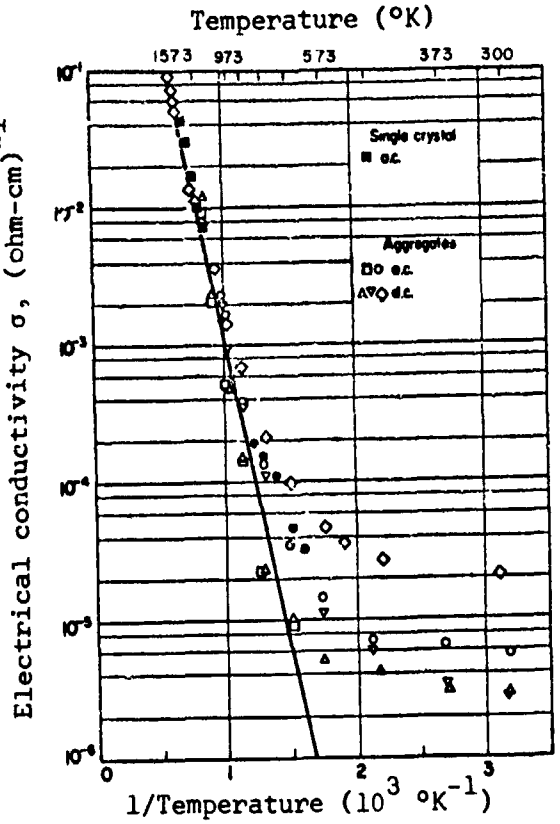


Electrical conductivity as a function of temperature for n-type, fairly pure, beta-silicon carbide.

[Ref. 17725]

SILICON CARBIDE

ELECTRICAL CONDUCTIVITY



Electrical conductivity as a function of temperature for beta-silicon carbide, both single crystal, and polycrystalline.

[Ref. 17416]

SILICON CARBIDE

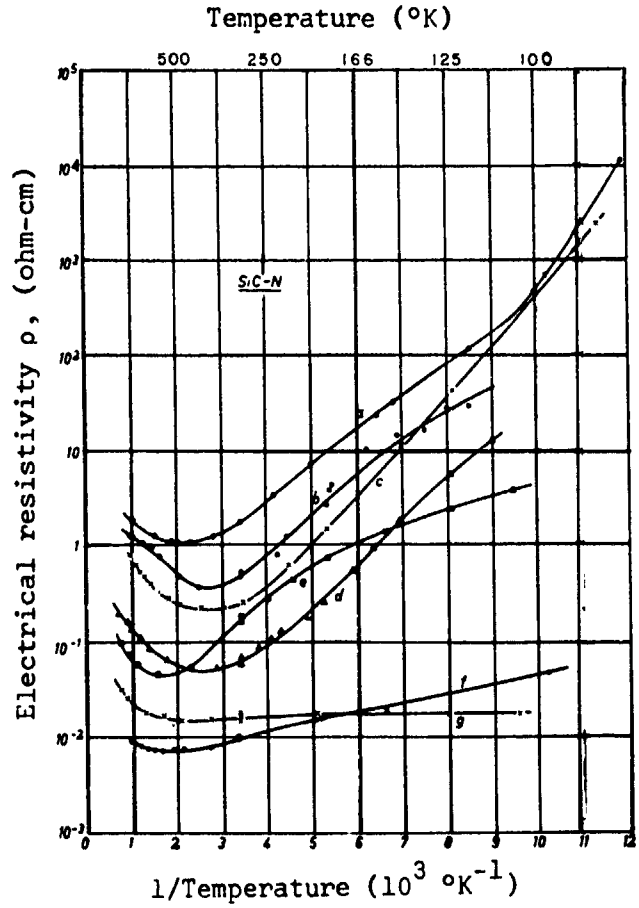
ELECTRICAL RESISTIVITY

Resistivity as a function of temperature for n-type, single crystal, alpha-silicon carbide.

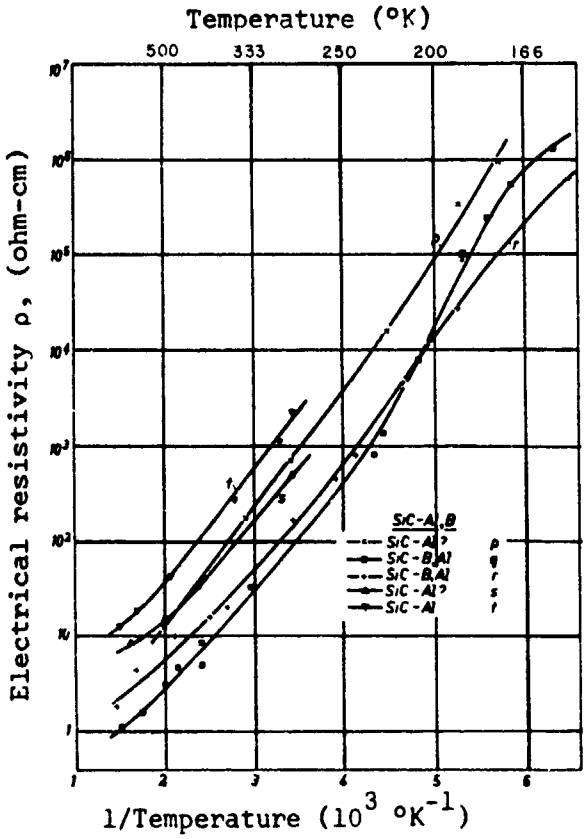
a) is grown in pure argon, no dopants, the other curves show increasing amounts of nitrogen,

n from 10^{17} to 5 x 10^{19}/cc.

d) and e) also have aluminum and boron impurities.



[Ref. 3608]



Resistivity as a function of temperature for single crystal, alpha-silicon carbide.

p) and s) are grown in pure argon
q) and r) in argon and boron
t) in argon + aluminum.

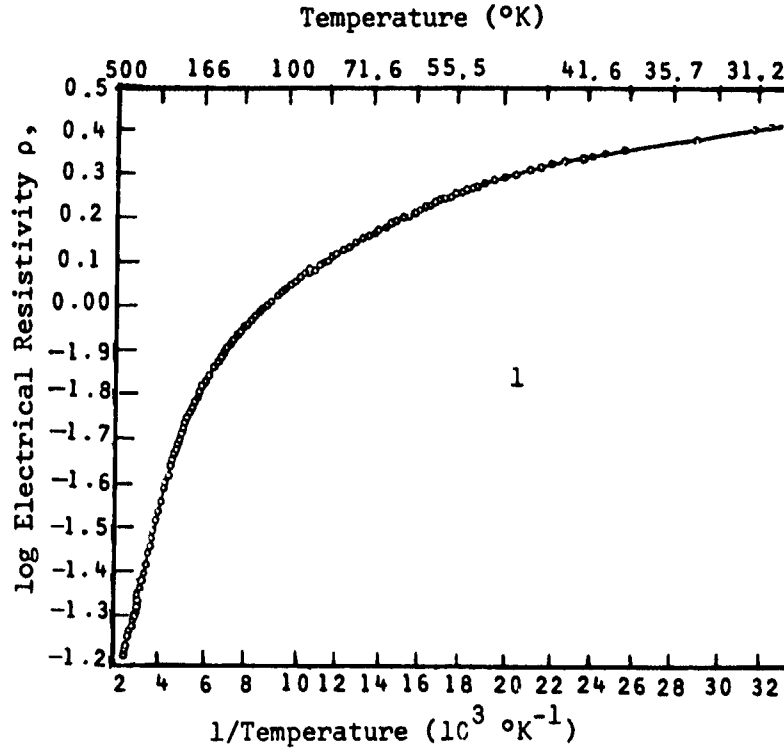
n varies from 10^{17} to 10^{18}/cc.

[Ref. 3608]

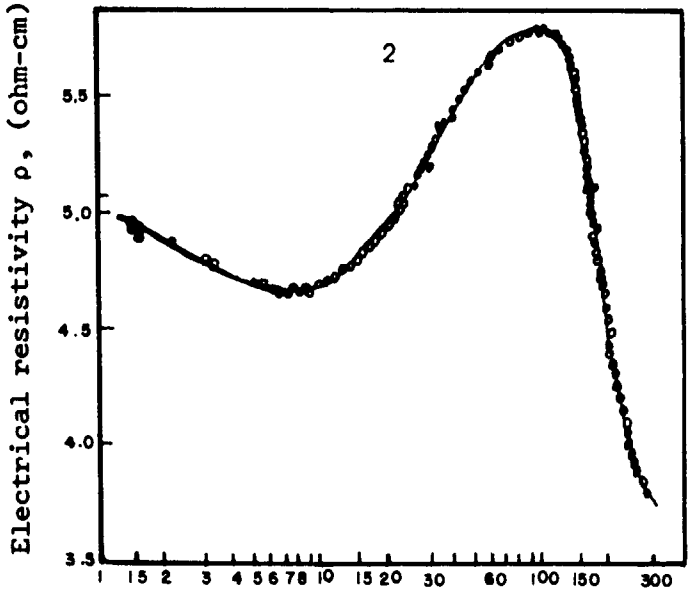
SILICON CARBIDE

ELECTRICAL RESISTIVITY

1) $n = 6.4 \times 10^{16}$/cc.



Resistivity as a function of temperature for n-type, single crystal, alpha-silicon carbide, fairly pure, slightly N-doped. [Ref. 17973]



2) $n = 3 \times 10^{17}$/cc.

[Ref. 17973]

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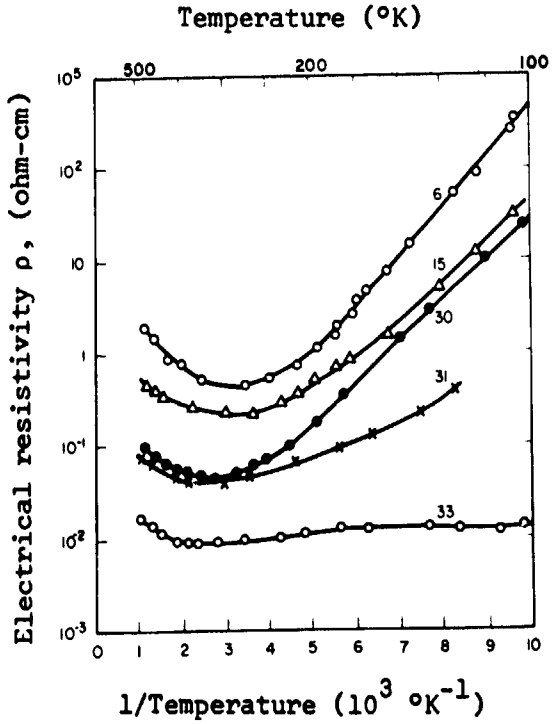
SILICON CARBIDE

ELECTRICAL RESISTIVITY

Resistivity as a function of temperature for n-type, single crystal, nitrogen-doped, alpha-silicon carbide, (6H).

carrier concentration
6 - 1. x 10^{17}/cc
15 - 4.5
30 - 30.
31 - 40.
33 - 200.



[Ref. 16397]

Approximate Resistivity (ohm-cm)	Dopant in Single crystal, β-SiC (ppm)	Crystal Type	Color	Temperature
0.5	60 B	p	green	300°K
10^{-1}	200 Al	p	blue-green	
10	< 10 Al	p	yellow-green	
10^3	no Al detected	n	light yellow	
10^3	no B detected	n	light yellow	

[Ref. 17725]

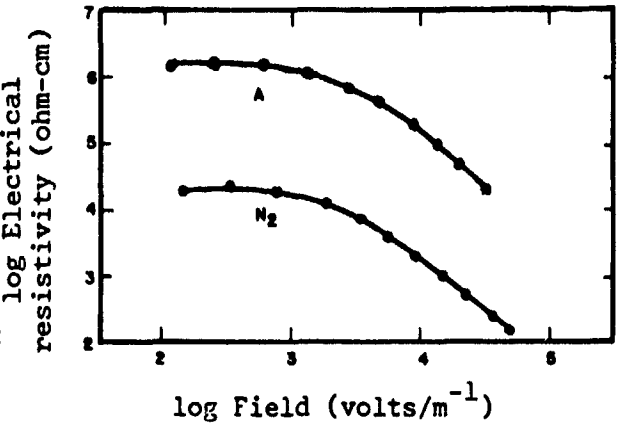
SILICON CARBIDE

ELECTRICAL RESISTIVITY

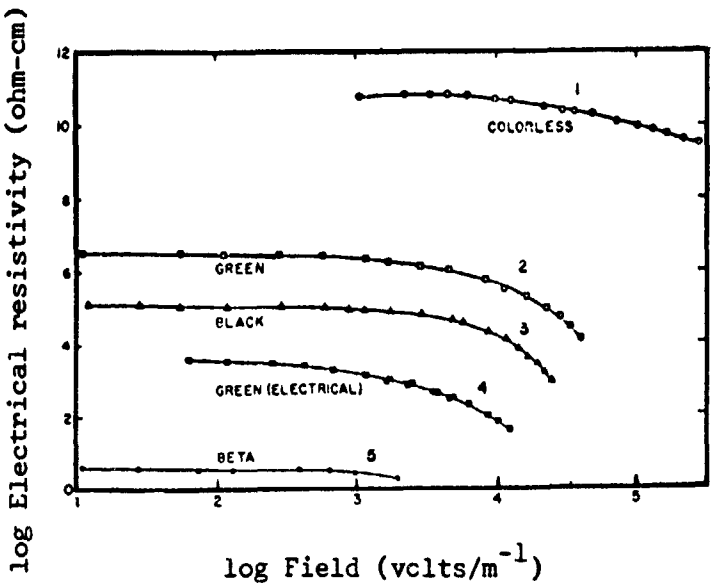
Log electrical resistivity as a function of electric field for pure, alpha-silicon carbide grains.

A - grains heated 2.5 hours at 1950°C in argon

N_2 - grains heated 2.5 hours at 1950°C in nitrogen gas.



[Ref. 17403]



Log electrical resistivity as a function of field for commercial silicon carbide grains.

1 to 4 are for alpha-SiC of varied impurity

5 is beta-silicon carbide grain.

[Ref. 17403]

SILICON CARBIDE

ELECTROACOUSTIC PROPERTIES

Pure, and nitrogen-doped, n-type, single crystal, α-SiC, (6H), at 6°K. $n = 10^{15}$ to 10^{17}/cc. Phonon energies in ev for various k vectors from luminescent data.

Phonon branch	$k_c = 2\pi/c$	$k_c = 4\pi/c$	$k_c = 6\pi/c$	
TA	.0335 .0363	.0392 .0403	.044 .0463	
LA	.0506 .0535	.0670 .069	.077	
TO	.0978	.0956	.0947	
LO	.107	.1055	.1042	[Ref. 6505]

Phonon branch	Value	Sample	Test Method	Temperature
LO	0.12 ev	n-type, N-doped, α-,	reflectivity data	300°K
TO	0.095			

[Ref. 3607]

SILICON CARBIDE

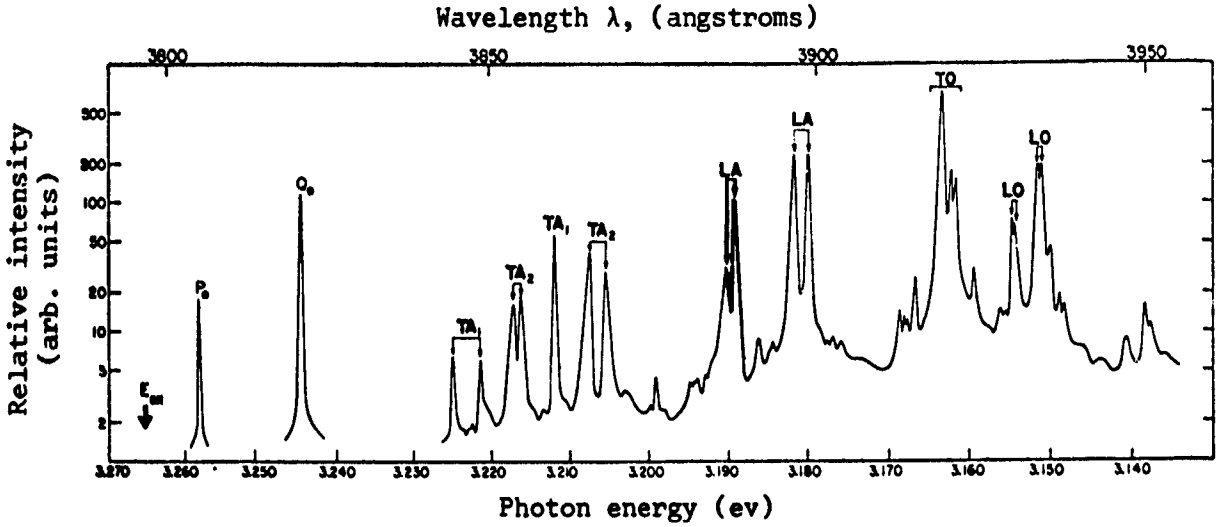
ELECTROACOUSTIC PROPERTIES

Phonon energies for single crystal, n-type, nitrogen-doped, α and β-silicon carbide at 6°K.

Phonon branch	β	α 15R	α 6H	Ref.
TA	.0463 ev	.0463 ev	.0463 ev	17405
LA	.0794	.0782	.077	
TO	.0944	.0946	.0947	
LO	.1028	.1037	.1042	17405
TA		.0344	.0335	13156
TA		.0350	.0363	
TA		.0393	.0392	
TA		.0397	.0403	
TA		.0432	.044	
TA		.0463	.0463	
LA		.0513	.0506	
LA		.0519	.0535	
LA		.0692	.067	
LA		.0702	.0690	
LA		.0782	.077	
TO		.0946	.0947	
TO		.0953	.0956	
TO		.0957	.0978	
TO		.0971		
LO		.1037	.1042	
LO		.1063	.1055	
LO		.1069	.107	13156

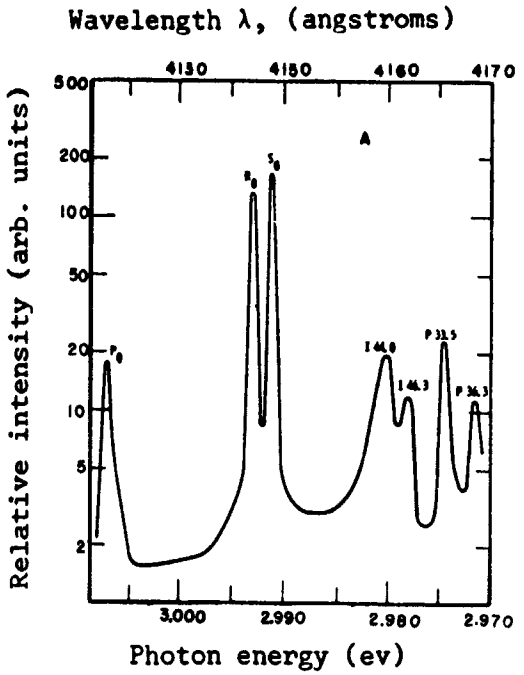
SILICON CARBIDE

ELECTROACOUSTIC PROPERTIES



[Ref. 17974]

Luminescence spectrum at 6°K of four-particle nitrogen-exciton complexes in single crystal, alpha-silicon carbide, (4H). P_0 and Q_0 are zero-phonon lines.



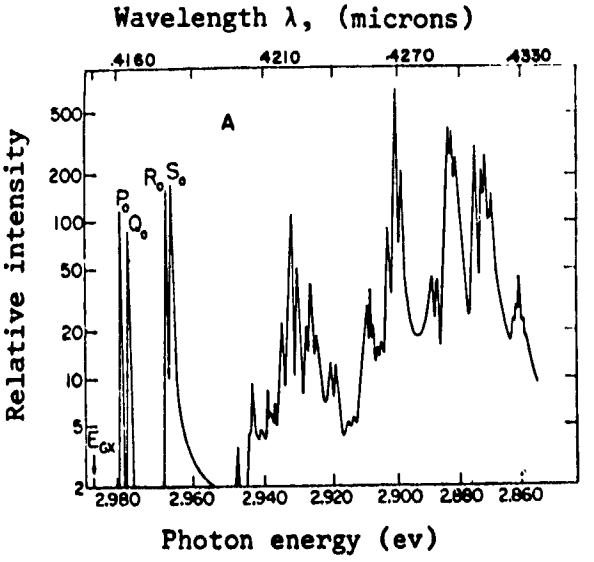
Luminescence spectrum of pure, single crystal, alpha-silicon carbide, (6H), at 6°K, $n = 10^{15}$/cc. The two additional intrinsic lines (I 44.0 & I 46.3) are due to recombination of free excitons.

[Ref. 6505]

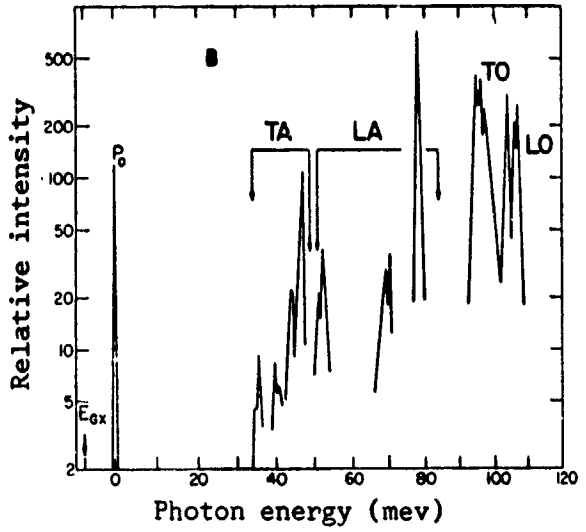
SILICON CARBIDE

ELECTROACOUSTIC PROPERTIES

Complete four-particle nitrogen-exciton luminescence spectrum at 6°K, for n-type, single crystal, alpha-silicon carbide, (15R). The four phonon-free lines are marked. Exciton energy gap = 2.98 ev.



[Ref. 13156]

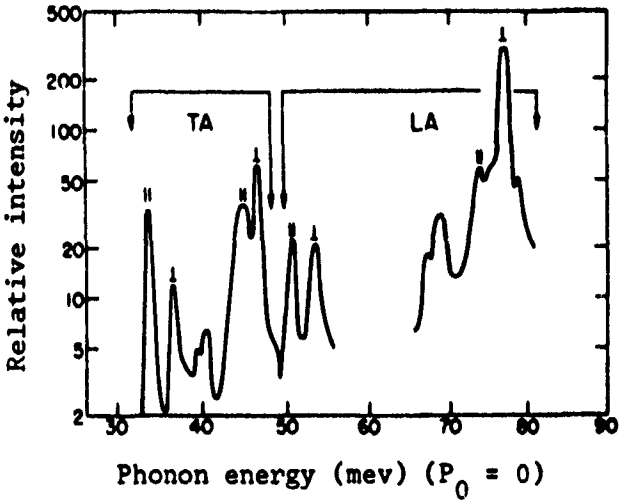


One of the four series of luminescence lines shown in the P series of A. The zero of energy has been placed at P_0, so that the energies of emitted phonons may be read directly.

[Ref. 13156]

SILICON CARBIDE

ELECTROACOUSTIC PROPERTIES



Samples are pure, single crystal, alpha-silicon carbide, (6H), at 6°K.

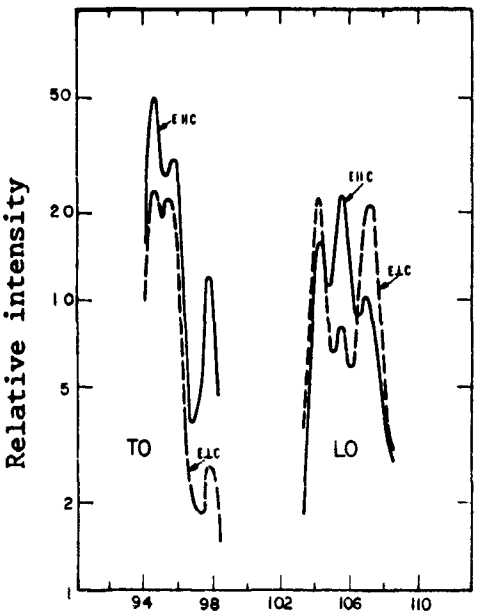
$n = 10^{15}$/cc.

—— Acoustic phonon lines

[Ref. 6505]

The phonon energy in ev represents the displacement of the energy from that of the phonon free line P_0. Polarization is parallel or normal to the c-axis.

Optical phonon lines ——



[Ref. 6505]

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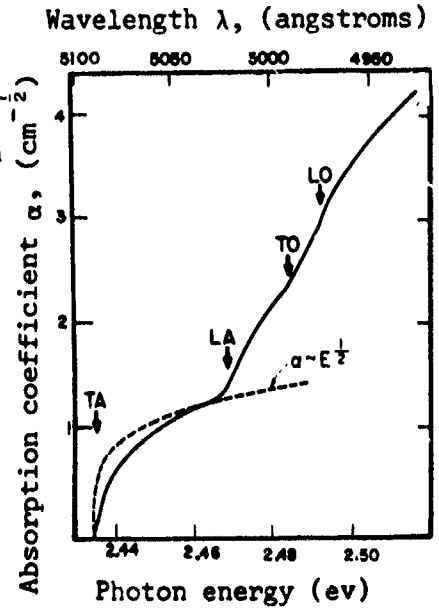
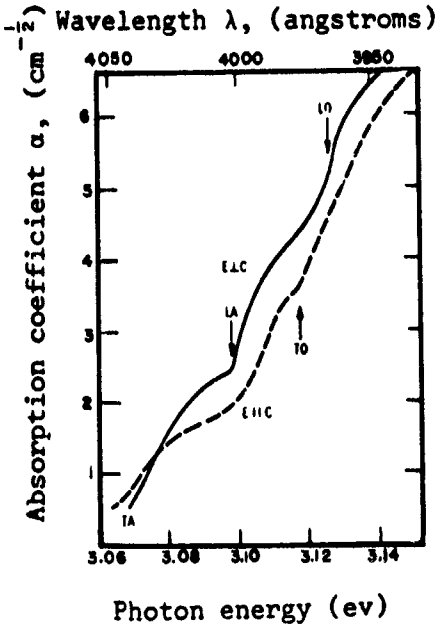
SILICON CARBIDE

ELECTROACOUSTIC PROPERTIES

Absorption edge of single crystal, n-type, beta-silicon carbide, at 4.2°K. Arrows indicate possible phonon emission. Exciton energy gap is 2.39 ev.



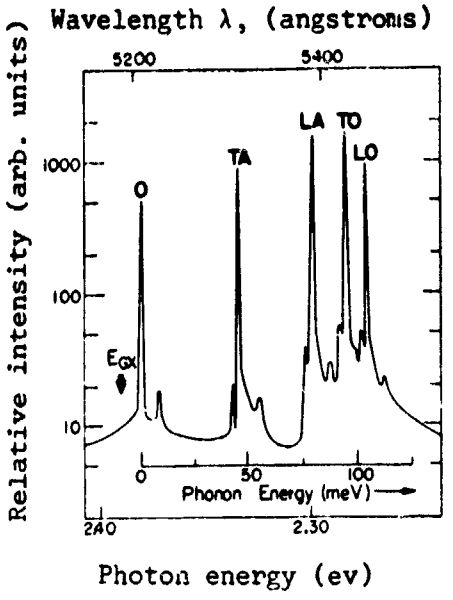
[Ref. 17405]



[Ref. 6505]

Absorption edges of pure, n-type, single crystal, alpha-silicon carbide, (6H), in polarized light at 77°K.
$n = 10^{15}$/cc.

The luminescence spectrum of four-particle nitrogen-exciton comples in single crystal, beta-silicon carbide at 6°K. The phonon branch energies may be read directly from the (mev) scale with 0 = phonon-free line.



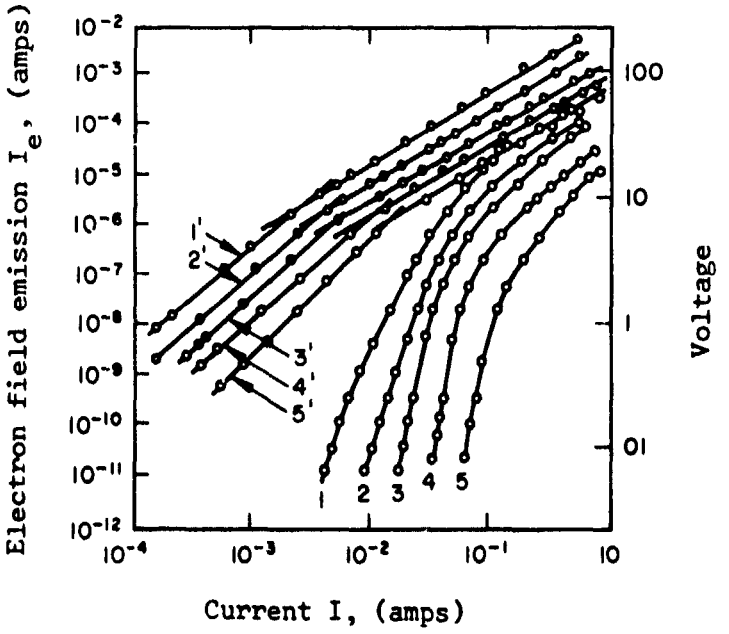
[Ref. 17405]

SILICON CARBIDE

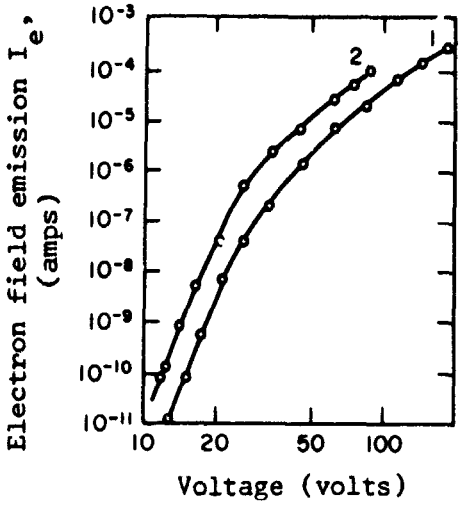
ELECTRON-FIELD EMISSION

Electron emission as a function of field in single crystal, alpha-silicon carbide p-n junction, formed by boron diffusion, (curves 1 to 5).

Voltage-current characteristics for the same sample are shown by curves 1′ to 5′.



[Ref. 17414]



Electron emission as a function of field for single crystal, alpha-silicon carbide p-n junction at two temperatures.

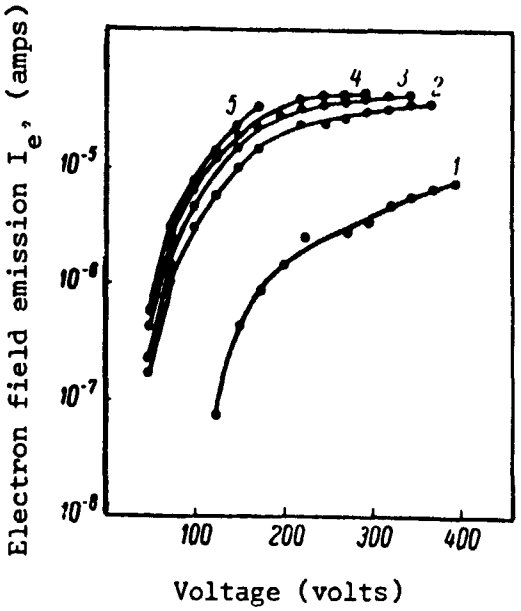
1 - 293°K

2 - 673°K

[Ref. 17414]

SILICON CARBIDE

ELECTRON-FIELD EMISSION



Electron emission as a function of field for single crystal, alpha-silicon carbide p-n junction.

1 - 293°K

2 - 473°K

3 - 553°K

4 - 663°K

5 - 773°K

[Ref. 14663]

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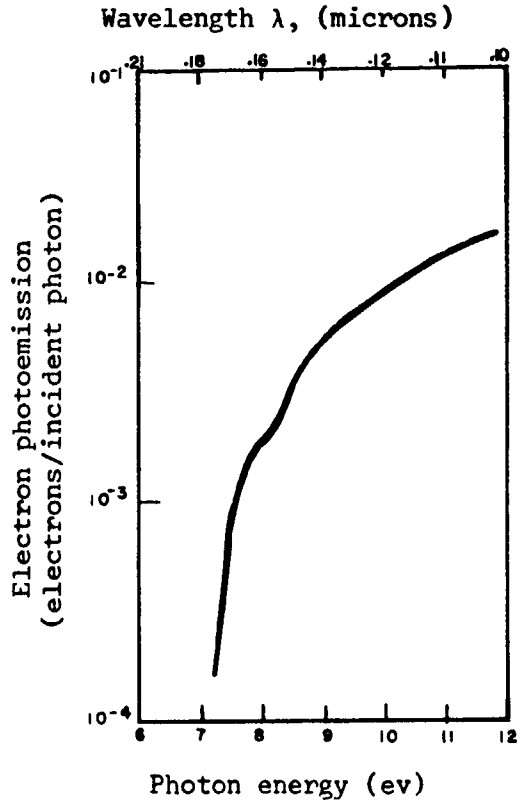
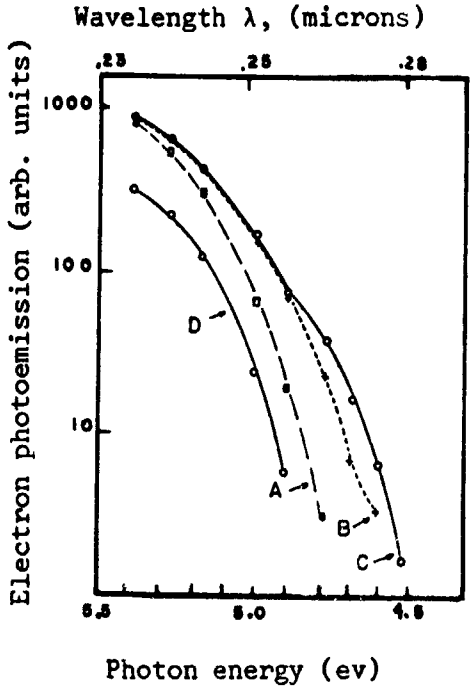
SILICON CARBIDE

ELECTRON PHOTOEMISSION

Electron photoemission as a function of wavelength for single crystal, (yellow color), beta-silicon carbide at 300°K.



[Ref. 787]



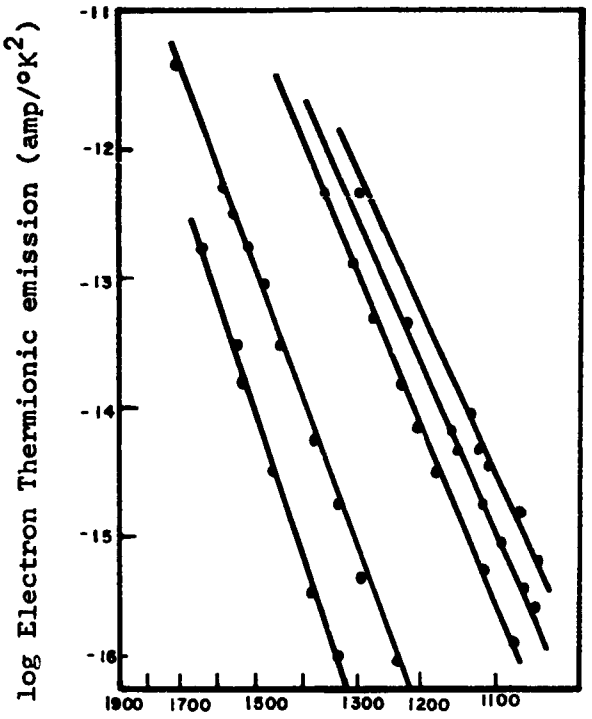
Electron photoemission as a function of wavelength in n-type, single crystal, (green color), alpha-silicon carbide at 300°K. ρ = 0.6 ohm-cm. The surfaces were variously treated by ion bombardment alone, and with annealing, as well as exposure to oxygen.

A - ion bombardment
B - ion bombardment + 1000°C anneal at 2 hrs.
C - ion bombardment + 1000°C anneal at 20 hrs.
D - oxygen exposure

[Ref. 7134]

SILICON CARBIDE

ELECTRON THERMIONIC-EMISSION



Electron thermionic emission in single crystal, alpha-silicon carbide, (commercial grade). Data at increasing temperatures are not reversible and fresh samples are required for each run.

[Ref. 7152]

SILICON CARBIDE

ENERGY BANDS

Symbol	Value (ev/°K)	Sample (single crystal)	Test Measurement	Temperature	Ref.
dEg/dT	$-5.8 \pm 0.3 \times 10^{-4}$	n-type, α-, n = 10^{17}/cc, ρ ∿ 0.1 ohm-cm	transmission at .885 to 428μ	295-700°K	18056
dEg/dT	-5×10^{-4}	n-type, α-, (6H), N-doped	10^4 oe, elec. resistivity, Hall meas. at 10 oe, also optical absorp. at .35 to 2.5μ	200-800°K	16397
	-1.2×10^{-4} at the 200 per cm absorp. band	n ∿ 10^{17}/cc (001) oriented			
dEg/dT	-3.3×10^{-4}	α-,	transmission and photoelectric	>300°K	17417
dEg/dT	-3 to -6×10^{-4}	n-, and p-type, α-.	photoconductivity λ = 0.6 to 5.5 ev	80-800°K	10994
	-3 to -4×10^{-4}	"	p-n junction photo-effect	"	
dEg/dT	-3.3 to 3.4×10^{-4}	n-type, α-, (6H), (001) oriented, ρ_{300K} = 7.5 ohm-cm	absorption	100°K, 293°K, & 500°K	4596
dI/dT	$-3.8 \pm 0.6 \times 10^{-4}$		photoconductivity		4596

E_{dc}	11.5 ev	p-type, α-, (6H). pure, (argon atmos.) Cl in argon, Al, O_2, N impurity in all	300-1300°K	8783
E_{dv}	13			

E_{dc} = deformation potential of conduction band

E_{dv} = deformation potential of valence band

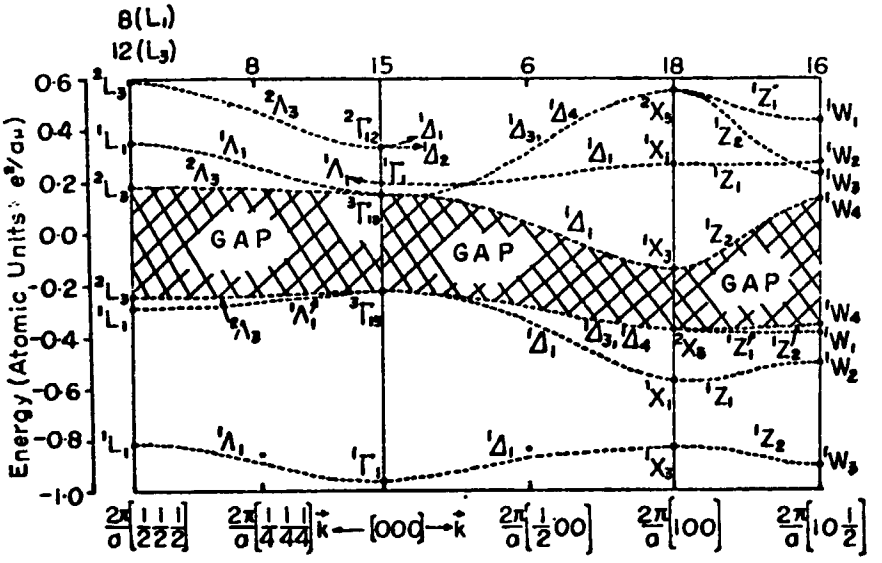
SILICON CARBIDE

ENERGY BANDS

Symbol	Value (ev/°K)	Sample (single crystal)	Test Measurement	Temperature	Ref.
E_1-E_2	.0048 ev	spin orbit splitting of valence band	photolum.	6°K	6505
kθ 1 phonon energy	0.09 ev	indirect transition in an α-, (6H) sample	transmission and photoelectric	77-717°K	17417

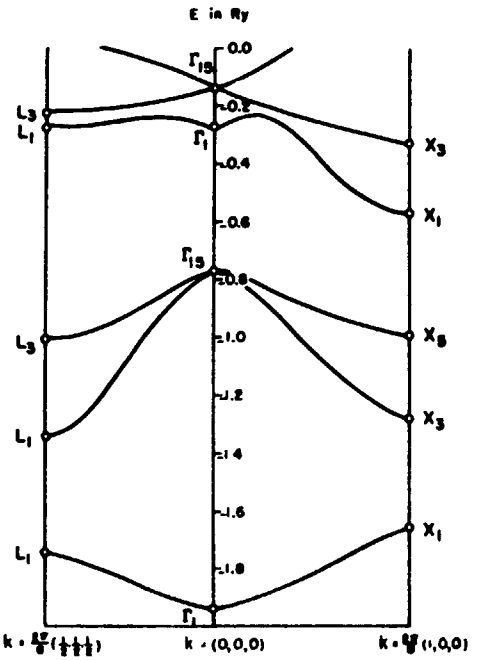
SILICON CARBIDE

ENERGY BANDS



Energy band structure of beta silicon carbide crystal obtained by OPW-calculation. The numbers at the top side of the figure represent those of the OPW-terms involved.
[Ref. 2348]

Ry	ev
.2	2.7
.4	5.4
.6	8.1
.8	10.8
1.	13.5
1.2	16.2
1.4	18.9
1.6	21.6
1.8	24.3



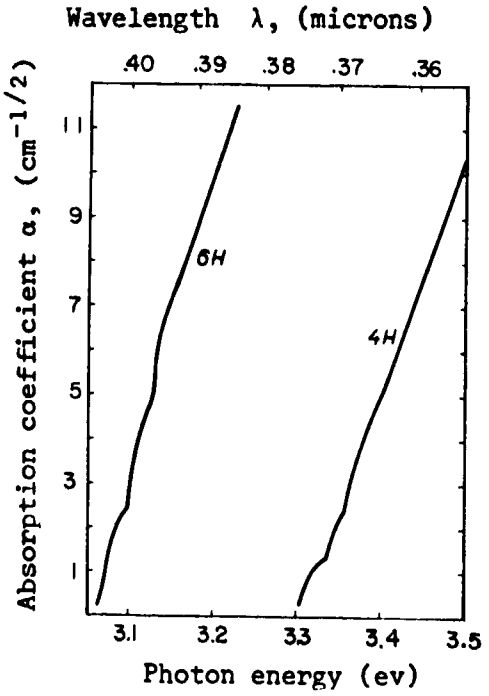
Band structure of silicon carbide. The computed values for the electronic states at the symmetry points Γ, L, and X are indicated by circles. The lines indicate the expected band profiles in the directions Λ and Δ.

[Ref. 14587]

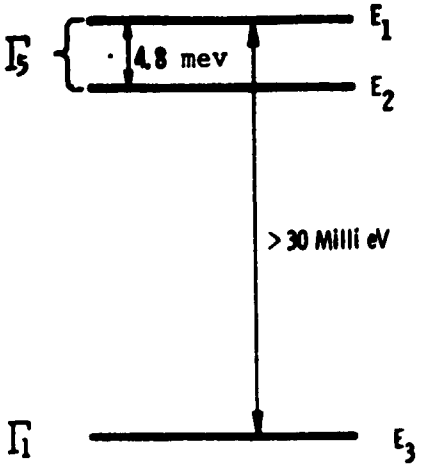
SILICON CARBIDE

ENERGY BANDS

Effect on energy gap of crystalline, polytype. Two samples of alpha silicon carbide, (6H) and (4H), are measured at 77°K, E normal to c-axis.



[Ref. 8792]

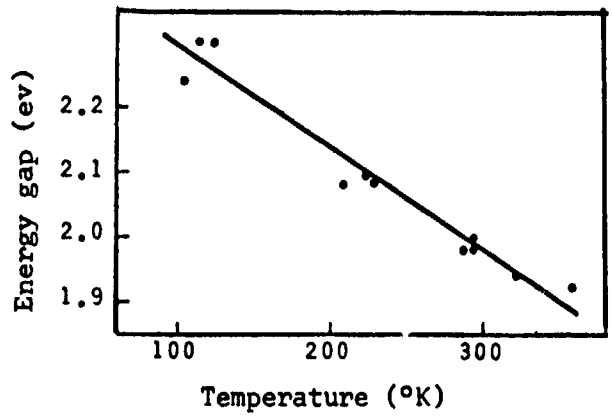


Observed splittings of the three valence bands in silicon carbide. The small spin-orbit interaction splits E_1 and E_2, and a much larger crystal field interaction splits off E_3.

[Ref. 6505]

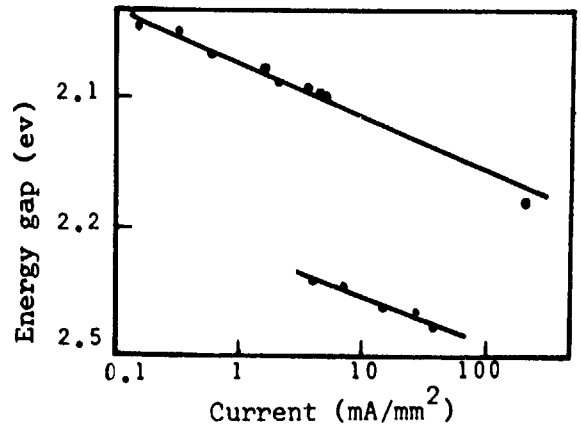
SILICON CARBIDE

ENERGY BANDS



Shift in energy gap as a function of temperature at constant current density for lightly coloured p- and n-type single crystal alpha silicon carbide.

[Ref. 2514]



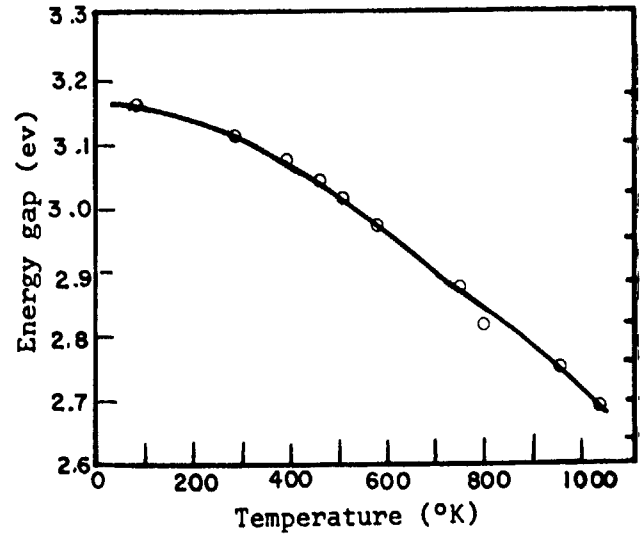
Shift in energy gap as a function of current density for lightly coloured p- and n-type single crystal alpha silicon carbide.

[Ref. 2514]

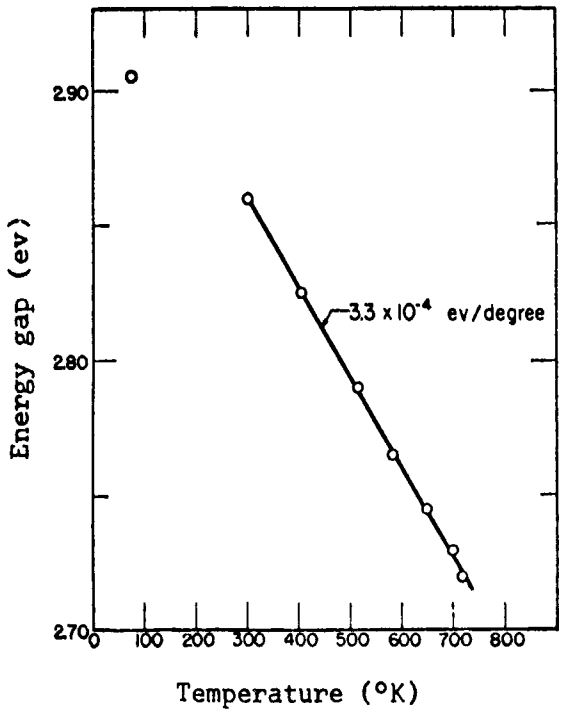
SILICON CARBIDE

ENERGY BANDS

Energy gap as a function of temperature for pure, colorless, alpha-silicon carbide.



[Ref. 3607]



Shift in energy gap as a function of temperature for alpha-silicon carbide.

[Ref. 17417]

SILICON CARBIDE

ENERGY GAP

Symbol	Value (ev)	Sample (single crystal)	Test Measurement	Temperature	Ref.
E_g	3.12	α-, (6H)	optical absorp.	300°K	787
	2.62	pure, β-,	"	"	787
	2.86	α-, (6H)	"	"	17419
	2.2	β-,	"	"	17419
	3.1 ± 0.2	n-type, α-,	conductivity, from 950-2000°K	0°K	17455
	∿ 3	pure, colorless, α-,	optical absorp.	300°K	3607
	∿ 2.8	yellow, β-,	"	"	3607
	2.986	n-type, N-doped, α-, (15R)	luminescence	6°K	13156
	2.86	α-,	optical	300°K	17417
	2.83 ± 0.1	p-n junction	radiation recomb.	300°K	7333
	2.8	n-type, green, $\rho = 10^2$ ohm-cm p-type, colorless, $\rho = 10^4$ ohm-cm	transmission at .22-.1 micron	300°K	2863

SILICON CARBIDE

ENERGY LEVELS

Explanation of Symbols used in Energy Levels Table

VB - distance above valence band in ev

CB - distance below conduction band in ev

E_C - conduction band edge

E_V - valence band edge

E_F - Fermi level

E_D - donor ionization energy level

E_A - acceptor ionization energy level

E_{Gx} - exciton energy gap

E_{peak} - photon energy at emission peak

Symbol	Value (ev)	Dopant	Sample (single crystal)	Test Measurement	Temperature	Ref.
E_D	0.02	N	n-type, β-,	electrical conductivity		17725
E_D	0.09	N	n-type, α-,	"		17725
E_D		N	n-type, α-, (6H)	Hall & resistivity	100-1000°K	16397
			$n = 10^{17}$/cc	meas. at 10^4 oe		
	0.086		ρ = .425 ohm-cm			
	0.063		ρ = 0.2 ohm-cm			
	0.23		ρ = 0.048 ohm-cm			16397
E_D	0.17	N	n-type, α-, (6H)	photoluminescence	77°K	11725
	0.20	N	"	"	"	
	0.23	N	"	"	"	11725

SILICON CARBIDE

ENERGY LEVELS

Symbol	Value (ev)	Dopant	Sample (single crystals)	Test Measurements	Temperature	Ref.
E_A	0.21	Al & 1 Mev electrons	n-type, $\rho \sim 0.5$ ohm-cm, $n \sim 10^{18}$/cc	Hall measurements		15717
	0.22		$n \sim 10^{18}$	radiation recombination		
	0.23		$n \sim 7 \times 10^{17}$	Hall measurements		
	0.25		$n \sim 7 \times 10^{17}$	radiation recombination		15717
E_D	0.47	fast neutron flux $10^{17}/cm^2$	n-type	resistivity measurement	300°K	*
E_A	0.24		p-type			
E_F	0.63		p-n junction, α-, $n \sim 8 \times 10^{17}$/cc	calculated from radiation recomb. & resistivity meas.	673°K	7333
E_F	0.52				300°K	
E_F	0.47 to 0.54		$\rho = 10^5$ ohm-cm		300°K	7333

Symbol		Sample, Resistivity and Colour		Test Measurements	Temperature	Ref.
E_1	E_2	n-type, α-, single transparent crystals		electrical conductivity		6080
1.57		10^{13} ohm-cm	pale yellow	↑	>1300°K	
0.441		10^3	pale yellow-green	|	1100°K	
0.304		10	pale green	|	625°K	
0.263	0.147	1	dark green	|	565°K	
0.198	0.097	.3	dark green	↓	480°K	
		p-type, α-, opaque				
0.2	0.5	1 ohm-cm			∿1000°K	6080

'* CENTRE D' ETUDE DE L' ENERGIE NUCLEAIRE. MOL, BELGIUM. Solid State Neutron Detector. QR No. 6, Jan. 1 - Mar. 31, 1962. EURAEC-306. Contract No. 079-61-10RDB. 1962.

SILICON CARBIDE

ENERGY LEVELS

Symbol	Value (ev)	Dopant	Sample (single crystal)	Test Measurement	Temperature	Ref.
E_D	0.14	N	n-type, α-, (15R)	optical absorption and luminescence	6°K	13156
	0.16	N				
	0.20	N				13156
E_D	0.6	N	n-type, α-, $n \sim 10^{18}$/cc	Hall and conductivity meas.		3608
	0.8_{CB}		$n \sim 10^{17}$/cc			3608

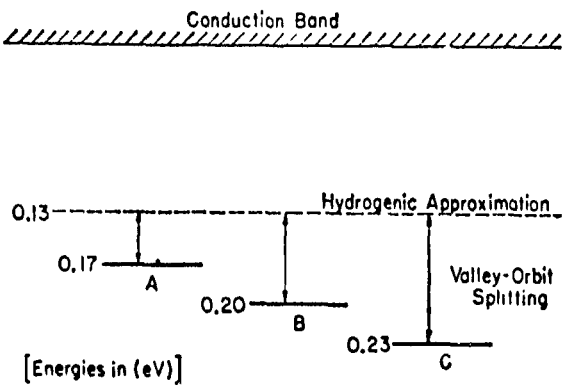
$E_{Gx}-E_{peak}$	E_{Gx}	E_{peak}	Emission Color	Sample B- & N-doped, α-, powders	Test Measurement	Temp.	Ref.
0.95 ev	3.263 ev	2.317 ev	green	(4H)	photo-	300°K	17404
0.89	3.023	2.137	yellow	(6H)	luminescence		
0.91	3.01	2.101	orange	(33R)	at		
0.94	2.986	2.049	orange-red	(15R)	.365 microns		
0.88	2.86	1.983	red	(21R)			
0.91	2.80	(1.89)		(8H)			
0.91	2.390	(1.48)		(3C)			17404

E_A	0.27_{VB}	Al	p-type, α-,	Hall & electrical	300-1300°K	8783
E_A	0.39_{VB}		"	resistivity	"	8783
E_A	0.275_{VB}	Al	p-type, α-, $n < 10^{18}$/cc	Hall & conductivity measurement		3608
	0.15	N	n-type, α-,	glow curve data	106°K	3607
	0.20	Al	p-type, α-,	"	233°K	3607
E_D	0.085_{CB}	N	n-type, α-,	fluorescence	77°K	3607
E_A	0.27_{VB}		p-type, α-,	"	"	3607

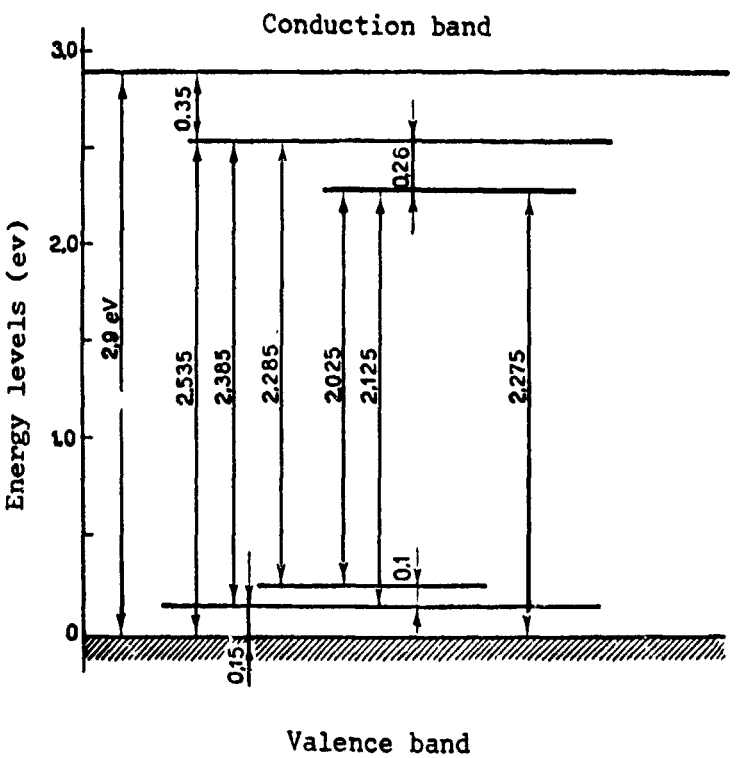
SILICON CARBIDE

ENERGY LEVELS

Energy level diagram showing the relation of the three nitrogen donor levels [A, B, and C] to that obtained by the hydrogenic approximation. The difference between 0.13 ev and a donor level may be taken as a rough measure of the valley-orbit splitting for that donor.



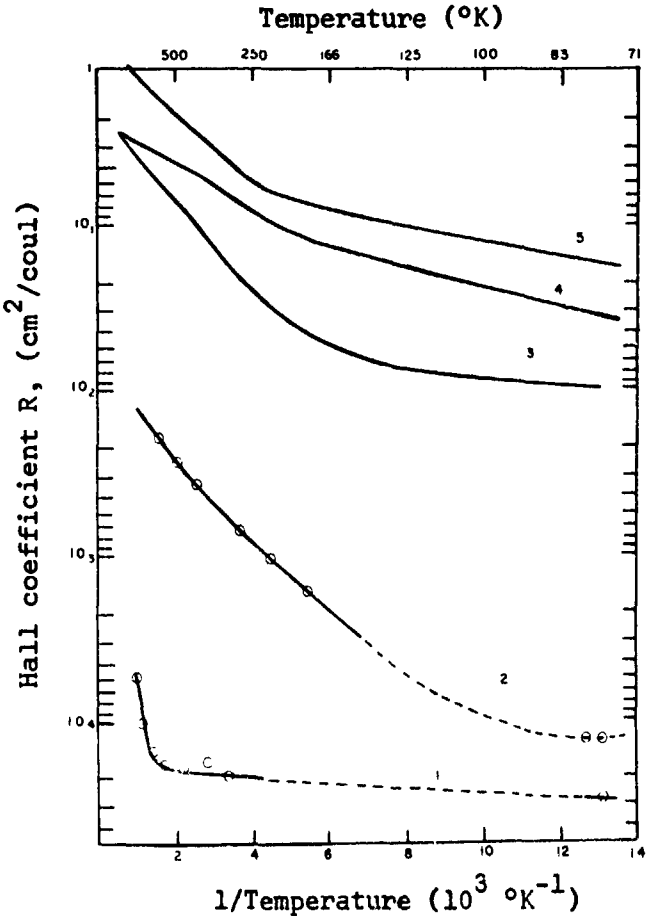
[Ref. 11725]



Energy level diagram for electroluminescence in silicon carbide. [Ref. 2899]

SILICON CARBIDE

HALL COEFFICIENT



[Ref. 5464]

Hall coefficient as a function of temperature for pure, n-type, single crystal, alpha-silicon carbide.

1 - $n \sim 10^{14}$/cc	ρ_{300K}	40 ohm-cm
2 - increasing n_i		2
3 -		.1
4 -		.04
5 - $n \sim 10^{16}$/cc		.1

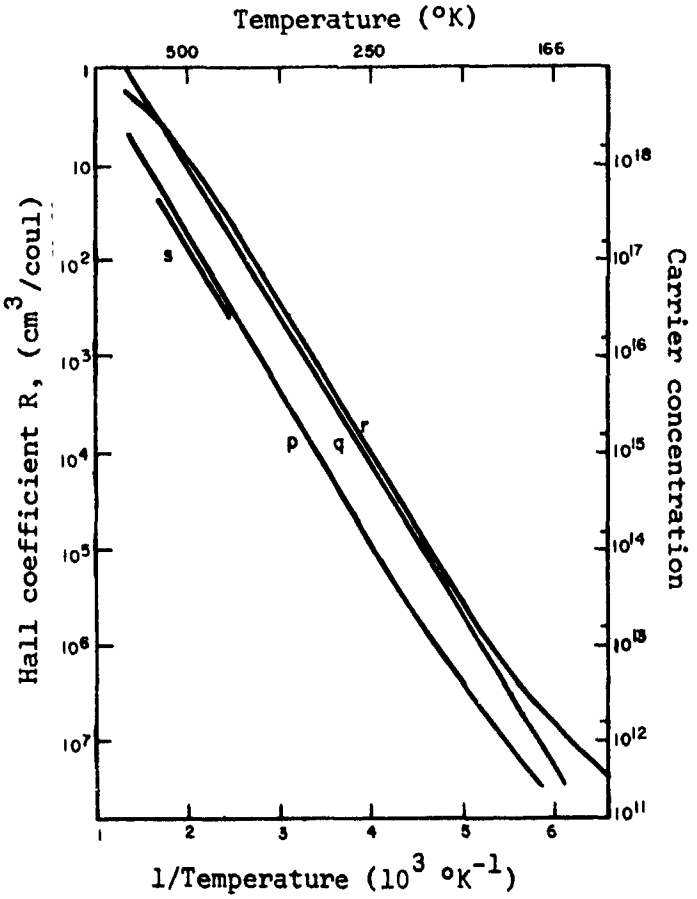
Dotted lines indicate no experimental points.

SILICON CARBIDE

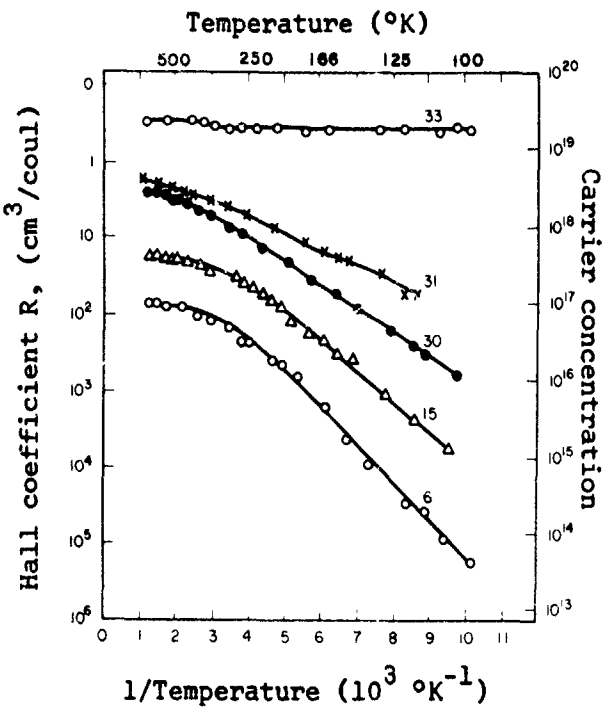
HALL COEFFICIENT

Hall coefficient as a function of temperature for p-type, single crystal, alpha-silicon carbide, (prepared in argon, argon + boron chloride and argon + aluminum chloride).

p - undoped	n $\sim 10^{17}$/cc
q - B-doped	n = 2.3×10^{17}
r - "	n = 9.5×10^{17}
s - Al-doped	n = 10^{18}



[Ref. 3608]



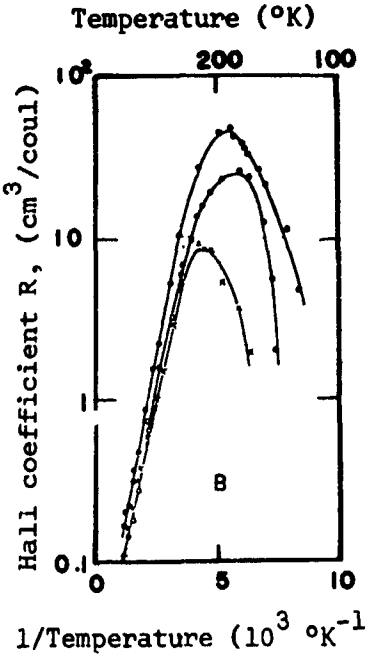
Hall coefficient as a function of temperature for n-type, single crystal, alpha-silicon carbide, (6H).

6 -	ρ = .425 ohm-cm.,	n = 10^{17}/cc.
15 -	.2	4.5×10^{17}
30 -	.053	30×10^{17}
31 -	.048	40×10^{17}
33 -	.0085	200×10^{17}

[Ref. 16397]

SILICON CARBIDE

HALL COEFFICIENT



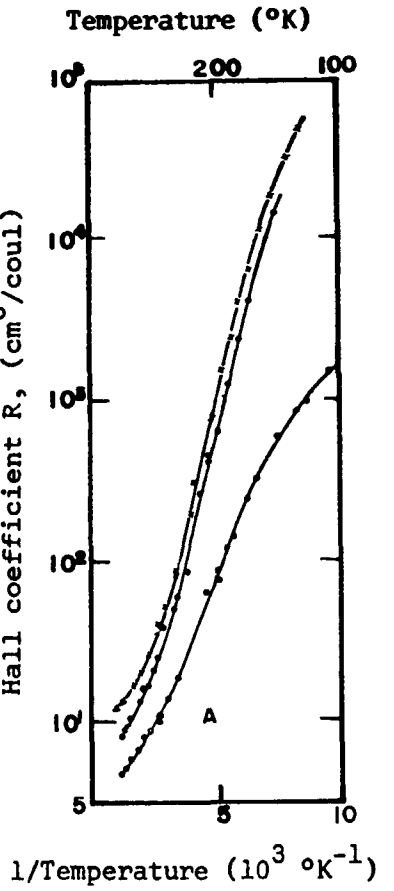
Hall coefficient as a function of temperature for single crystal, alpha-silicon carbide.

A - n-type, green

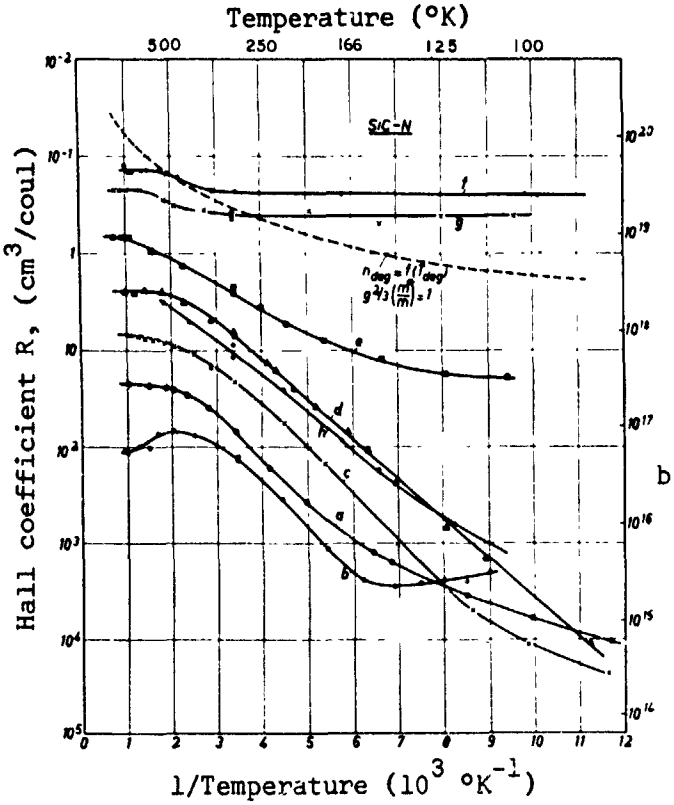
o - ρ = .12 ohm-cm at 480°K
x - ρ = 1.0 | 620°K
• - ρ = .5 | 570°K

B - p-type, black

$\rho_{1000K} \sim 0.05$ ohm-cm.



[Ref. 5990]



Hall coefficient as a function of temperature for n-type, alpha-silicon carbide, (prepared in argon, argon + nitrogen and for [h] argon, nitrogen and aluminum chloride).

a - undoped	$n = 3.6 \times 10^{17}$/cc.
b, c - N-, Al-, B-,	10^{18}
d -	10^{19}
e -	10^{19}
f - N-doped	$n = 5.0 \times 10^{19}$
g - "	$n_n = 3.4 \times 10^{19}$
h - N-, Al-doped	$n_n = 3.0 \times 10^{18}$

The dotted line is a theoretical curve.

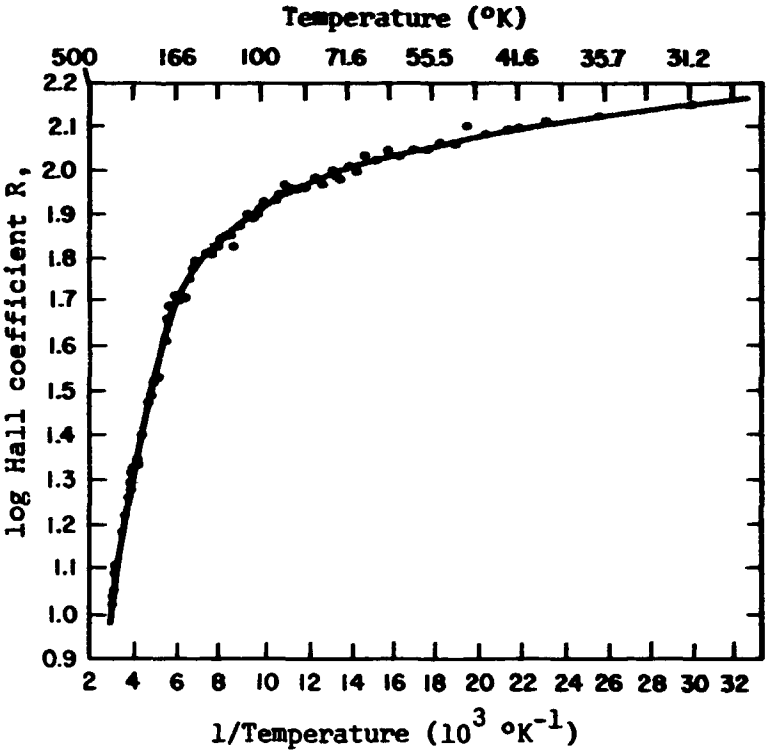
[Ref. 3608]

SILICON CARBIDE

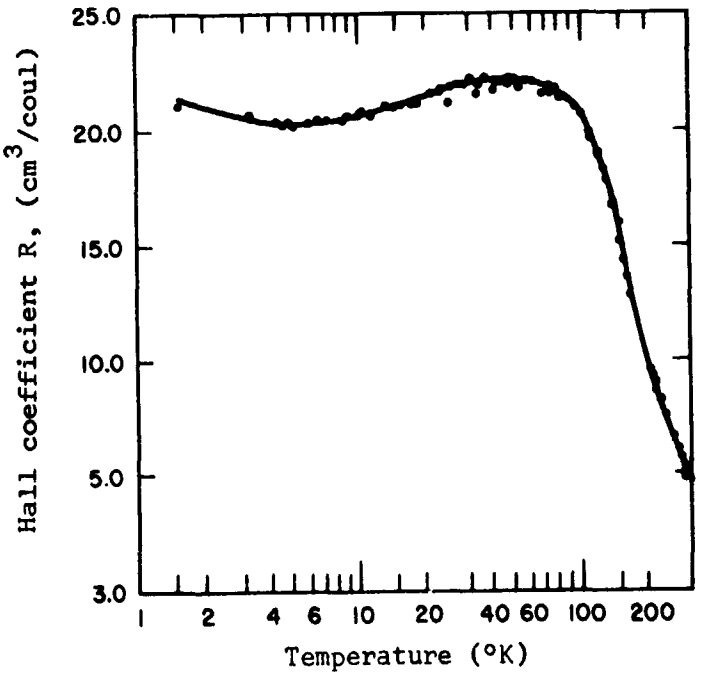
HALL COEFFICIENT

$n = 5.6 \times 10^{17}$/cc.

$\rho_{290K} = .222$ ohm-cm.



Hall coefficient as a function of temperature for n-type, single crystal, alpha-silicon carbide. [Ref. 17973]



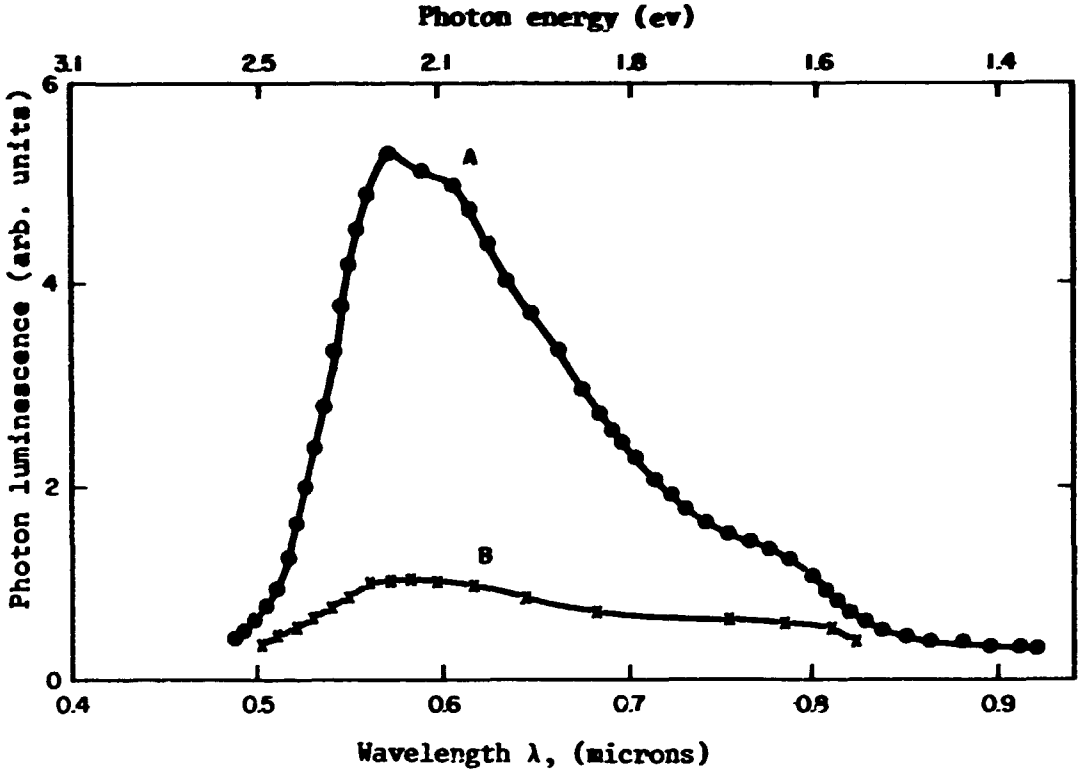
$n = 1.3 \times 10^{18}$/cc.

$\rho_{290K} = .0398$ ohm-cm.

[Ref. 17973]

SILICON CARBIDE

IRRADIATION PROPERTIES



Photoluminescence as a function of wavelength for p-type, single crystal, alpha-silicon carbide at 300°K. The samples were irradiated by 5×10^{11} neutrons/cm^2 sec.

A - characteristic fluorescence of aluminum-doped sample

B - after 10 minutes irradiation

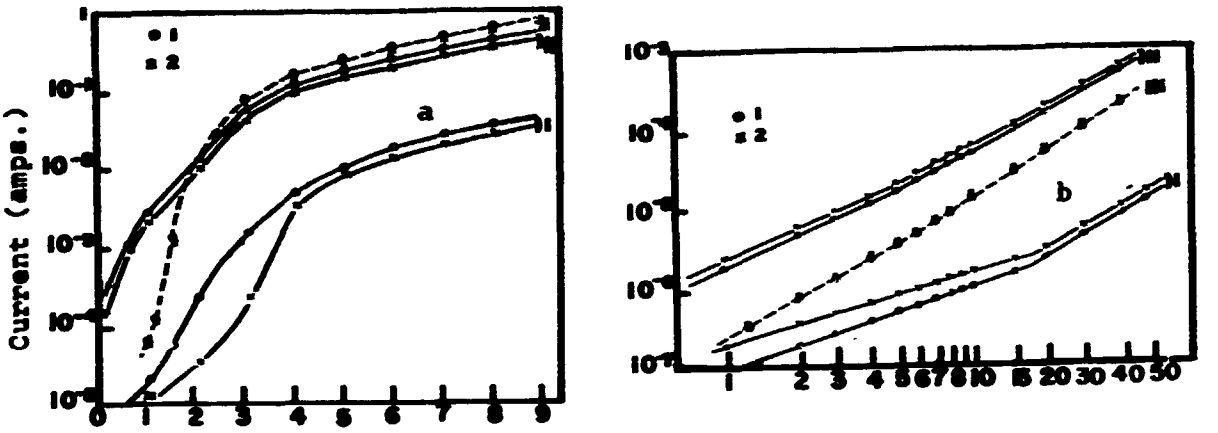
[Ref. 18349]

According to their original quality, silicon carbide diodes are affected by a fast neutron radiation flux of 10^{14}/cm^2 to 10^{16} or 10^{17}/cm^2. *

* CENTRE D' ETUDE DE L' ENERGIE NUCLEAIRE, BRUSSELS. Solid State Detector for Neutrons. QR No. 2, Jan. - Mar. 1961. EURAEC-107. 1961.

SILICON CARBIDE

IRRADIATION PROPERTIES



Current-voltage characteristics in the forward (a) and reverse (b) directions for unirradiated (1) and irradiated (2) single crystal, alpha-silicon carbide p-n junctions. The original material was n-type, n ∿ 5 x 10^{17}/cc. Radiation used is:

I - γ-rays
II - β-rays
III - γ-rays + neutrons

No change in current-voltage characteristics but a junction photoeffect occurs.
[Ref. 19624]

A fast neutron flux of 2.2 x 10^{17}/cm^2 changes p-type, single crystal, α-silicon carbide to n-type. n-Type remains unaffected by a 3.8 x 10^{16}/cm^2 flux. Optical transmission is only slightly affected by nvt_f = 10^{16}/cm^2 from .4 to 2.5 microns. 1 ohm-cm, n-type, α-silicon carbide, single crystal after 10^{16}/cm^2 neutron irradiation has 100 ohm-cm resistivity.

Mobility	Sample	Irradiation	Temperature	Ref.
15 cm^2/v sec	single crystal, p-type	non-irradiated	500°K	*
50 cm^2/v sec	single crystal, n-type	nvt_f = 10^{16}/cm^2	500°K	

* CENTRE D' ETUDE DE L' ENERGIE NUCLEAIRE. MOL, BELGIUM. Solid State Neutron Detector. QR No. 6, Jan. 1 - Mar. 31, 1962. EURAEC-306. Contract No. 079-61-10RDB. 1962.

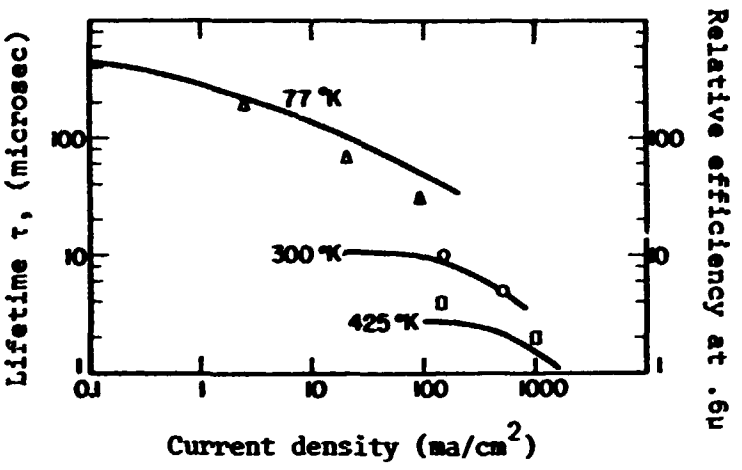
SILICON CARBIDE

LIFETIME

Symbol	Value (μsec)	Sample (single crystal)	Test Method	Temperature	Ref.
τ_p	80	p-n junction, α-,	recomb. radiation	133°K	2152
τ_p	1.15	"	"	300°K	2152
τ_p	∿ 30	n-type, α-,	photoconductivity	300°K	11441
τ_p	1.	p-n junction, α-,	recomb. radiation	300°K	7867
τ_p	30	p-type, boron-doped, α-, ρ = 11000 ohm-cm	current voltage	300°K	5908
τ_p	.3	n-type, pure, argon grown, white, α-, ρ = 5300 ohm-cm	"	"	5908
τ_p	.008 to .02	n-type, nitrogen-doped, α-, ρ = .2 to 10 ohm-cm	photoconductivity & electroluminescence	300°K	10533
τ_p	0.01	p-type, aluminum-doped, α-, to 90000 ohm-cm	"	300°K	10533
τ_p	.01 to 1.0	n-type, aluminum-doped, α-, $n \sim 10^{18}$/cc, ρ = .5 ohm-cm	recomb. radiation after 1 Mev electron irradiation	200-350°K	15717
τ_n	3	p-type, boron-doped, α-, ρ = 11000 ohm-cm	current voltage	300°K	5908
τ_n	< 0.5	p-n junction, α-,	electroluminescence	300°K	17421
τ_n	∿ .4	n-type, α-,	"	300°K	7805
	.1	"			
	.004	"			
	.009	p-type, α-,	"	"	7805
τ_n	.01	p-n junction, n-type, Al-doped $n_n \sim 10^{18}$/cc	electroluminescence	300°K	368
τ_n	.01 to .05	n- and p-type, aluminum-doped, β-,		300°K	17725
τ	<3	β-, single crystal & polycrystalline	electrical		17416

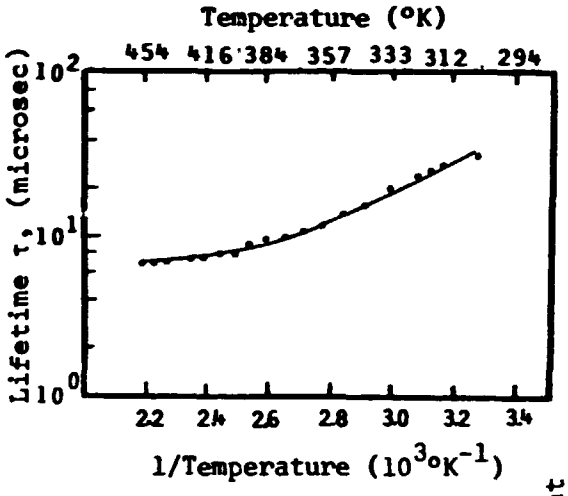
SILICON CARBIDE

LIFETIME



Lifetime as a function of current density for single crystal, alpha-silicon carbide, (p-n junctions). The points give the hole lifetime and the curves give, at the same temperatures, the relative number of photons per unit current, i.e., relative efficiency, at 6 microns. The curves are normalized to bring out the correlation with the hole lifetimes.

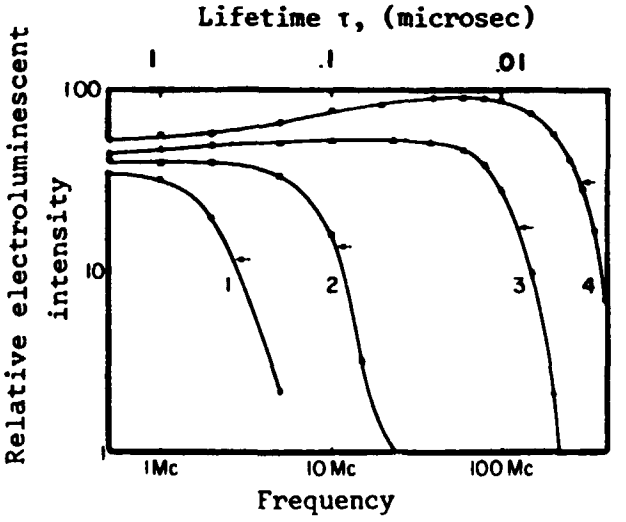
[Ref. 368]



Lifetime as a function of temperature for n-type, single crystal, alpha-silicon carbide; photoconductivity measurements.

[Ref. 11441]

Lifetime as a function of frequency for single crystal, alpha-silicon carbide at 300°K. 1, 2 and 4 are n-type, 3 is p-type. → indicate τ at 35% of maximum value.



[Ref. 7805]

SILICON CARBIDE

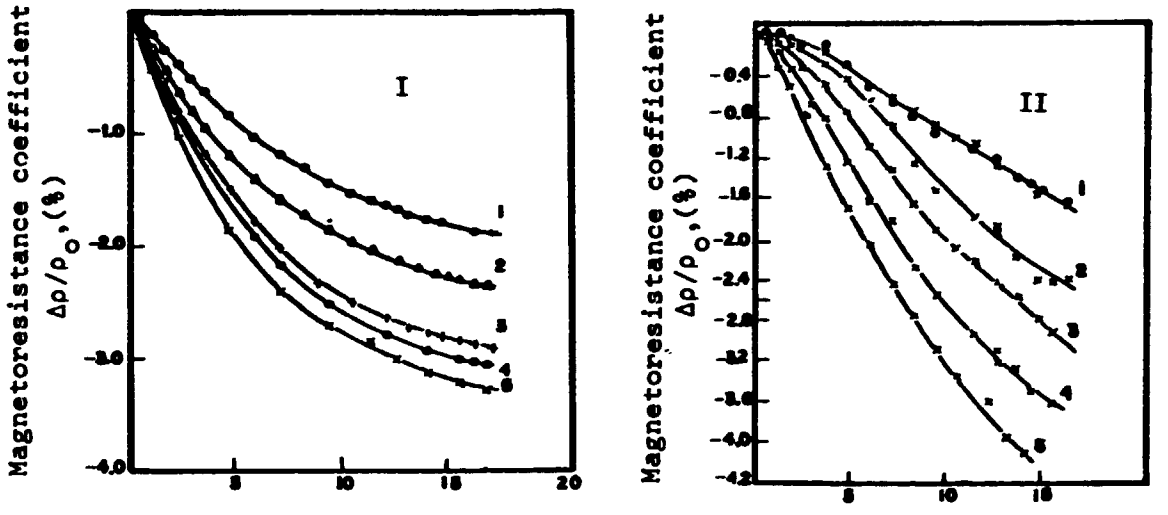
MAGNETIC SUSCEPTIBILITY

Symbol	Value	Sample (single crystal)	Test Method	Temperature	Ref.
	(mean value)				
χ	-12.8×10^{-6}/gm mol [0.316×10^{-6}/cgs units]	green, α-,	4640-6160 oe	300°K	13757
$\chi_{\perp}$	-13.1×10^{-6}/gm mol [-0.326×10^{-6}/cgs units]				13757
$\chi_{\perp}$	-5.4 to 8.2×10^{-6}/gm mol	black, α-,			13757
χ	-0.319×10^{-6}/cgs units				7359
$\chi_{\parallel}$ $\chi_{\perp}$	(magnetic anisotropy) 0.82×10^{-6}/gm mol [0.02×10^{-6}/cgs units]		3560-4250 oe	300°K	13757

Magnetic susceptibility is shown in both molar and cgs units.

SILICON CARBIDE

MAGNETOELECTRIC PROPERTIES



Magnetoresistance as a function of magnetic field for fairly pure, (slightly N-doped), n-type, alpha-silicon carbide.

I) $n = 3 \times 10^{17}$/cc

1 - 4.23°K
2 - 3.23°K
3 - 2.08°K
4 - 1.55°K
5 - 1.43°K

II) $n = 6.4 \times 10^{16}$/cc

1 - 4.21°K
2 - 3.10°K
3 - 2.54°K
4 - 2.01°K
5 - 1.63°K

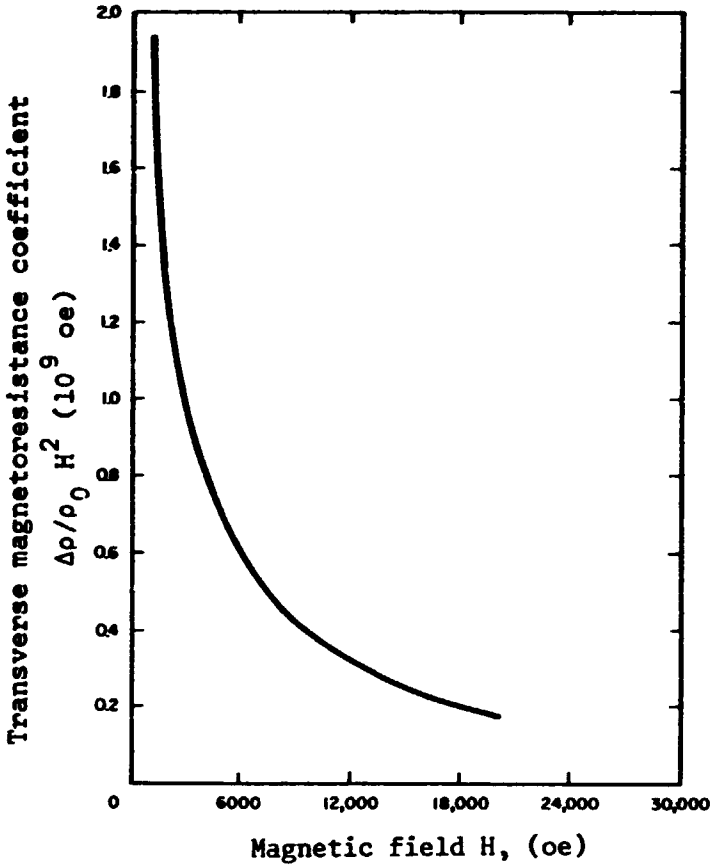
o and x are data taken with different probes.

[Ref. 17973]

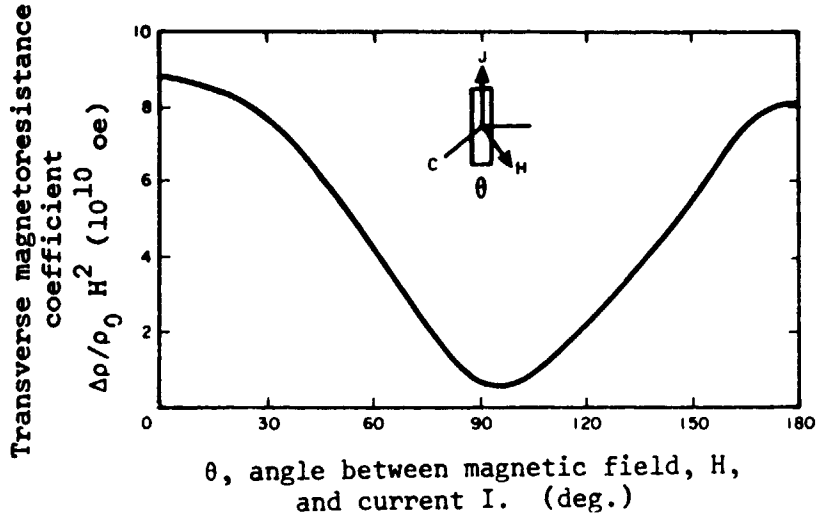
SILICON CARBIDE

MAGNETOELECTRIC PROPERTIES

Transverse magnetoresistance coefficient as a function of magnetic field in n-type, single crystal, alpha-silicon carbide at 77°K, H parallel to c-axis.



[Ref. 11132]



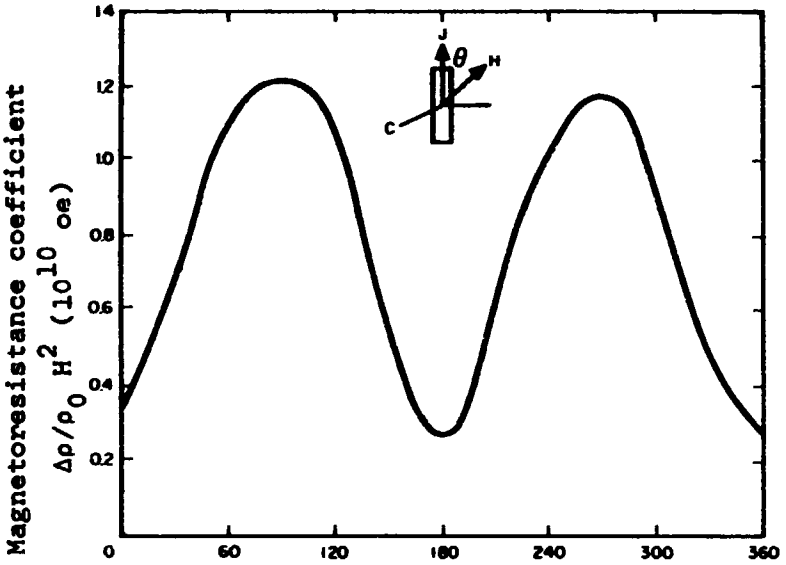
Transverse magnetoresistance coefficient as $\vec{H}$ is rotated with respect to $\vec{J}$ in n-type, single crystal, alpha-silicon carbide, at 77°K. H = 3900 oe.

[Ref. 11132]

SILICON CARBIDE

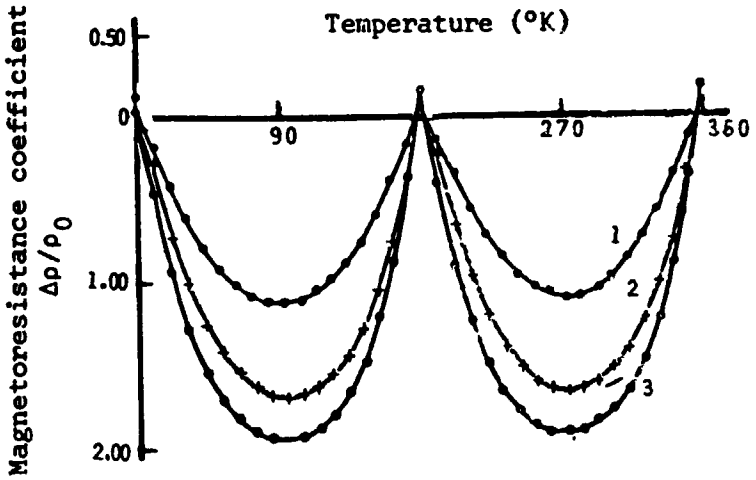
MAGNETOELECTRIC PROPERTIES

Magnetoresistance as a function of angle for n-type, single crystal, alpha-silicon carbide at 77°K and 3900 oe.



θ, angle between magnetic field, H, and current I. (deg.)

[Ref. 11132]



Magnetoresistance as a function of θ, angle between magnetic field and current for n-type, single crystal, alpha-silicon carbide at 4.22°K.

1 - 6.1 kc
2 - 11.6 kc
3 - 15.7 kc

[Ref. 17073]

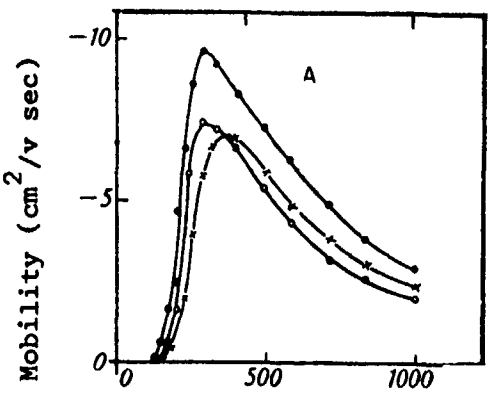
SILICON CARBIDE

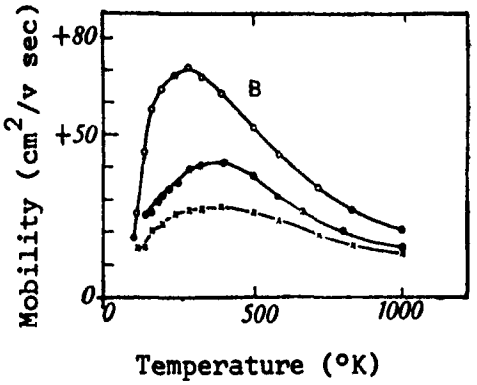
MOBILITY

Symbol	Value	Sample (single crystal) n /cc	ρ (ohm-cm)		Temperature	Ref.
μ	>2000	~ 10^{14}	10.	n-type, pure, α-, (6H)	77°K	5464
	400				300°K	
	40	~ 10^{16}	.3		77°K	
	38				300°K	5464
μ	360	2 x 10^{17}	.425	n-type, N-doped, α-, (6H)	293°K	16397
	160	1	.2			
	142	30	.053			
	90	40	.048			
	37	200	.0085			16397
μ	26		422.	p-type photo. meas. at	300°K	409
μ_n	2100	1.67 x 10^{16}	.179	n-type, very pure, β-,	300°K	17725
	3265	1.18 x 10^{16}	.163			
	4670	1.38 x 10^{15}	.971			17725
μ_n	150	1.3 x 10^{17}		n-type, N-doped, α-,	300°K	17233
	62	3.6 x 10^{17}			500°K	17233
μ_n	32		.00185	n-type, light green, β-,	300°K	17416
μ_n	220	< 10^{15}		n-type, pure, α-, (argon grown)	300°K	8783
μ_p	48					8783

SILICON CARBIDE

MOBILITY



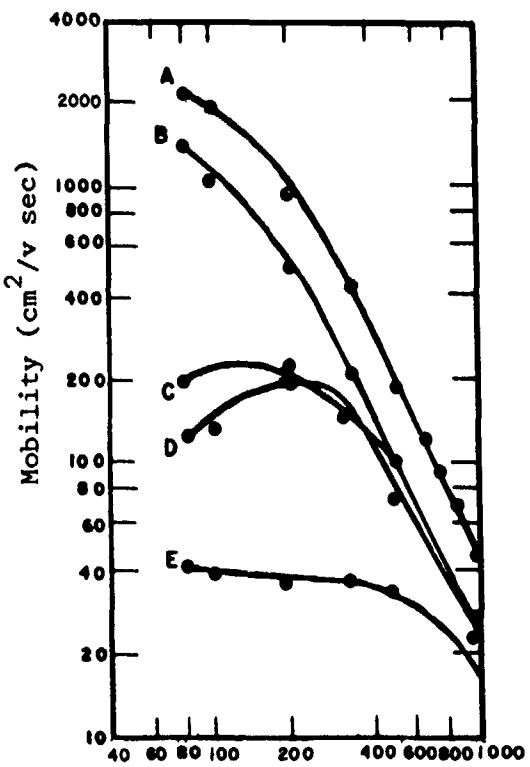


[Ref. 5990]

Mobility as a function of temperature for single crystal, alpha-silicon carbide.

A - p-type, black, $\rho_{1000K} \sim .05$ ohm-cm.

B - n-type, green, ρ = o .12 at 480°K; x 1.0 at 620°K; • .5 at 570°K



Mobility as a function of temperature for very pure, n-type, single crystal, alpha-silicon carbide, (6H).

	n /cc	ρ_{300K} ohm-cm
A	$\sim 10^{14}$	40.
B		2.
C		.1
D		.04
E	10^{16}	.1

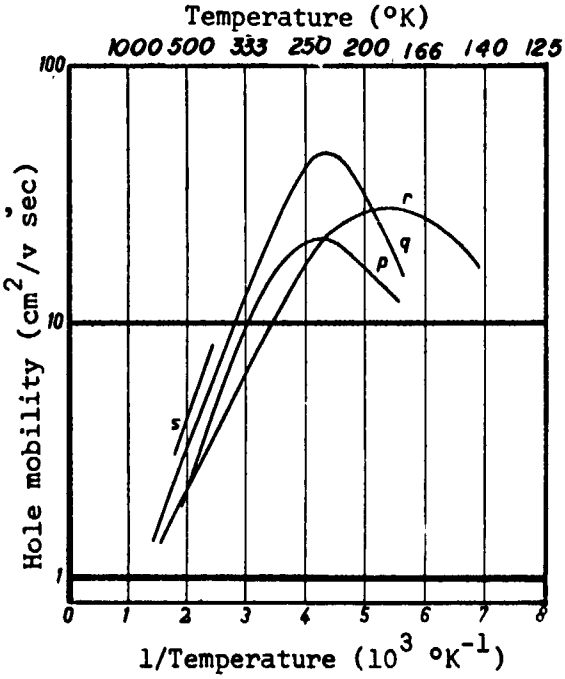
[Ref. 5464]

SILICON CARBIDE

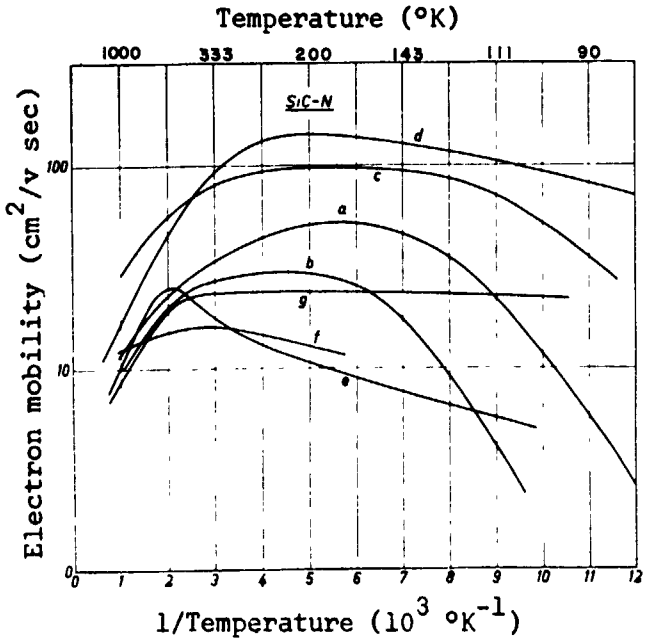
MOBILITY

Mobility as a function of temperature for p-type, single crystal, alpha-silicon carbide, prepared in argon, argon + boron chloride, and argon + aluminum chloride.

p - undoped $n \sim 10^{17}$/cc
q - Al-doped $n = 2.4 \times 10^{18}$
- B-doped $n = 2.3 \times 10^{17}$
r - Al-doped $n = 3.7 \times 10^{18}$
- B-doped $n = 9.5 \times 10^{17}$
s - Al-doped $n = 10^{18}$



[Ref. 3608]



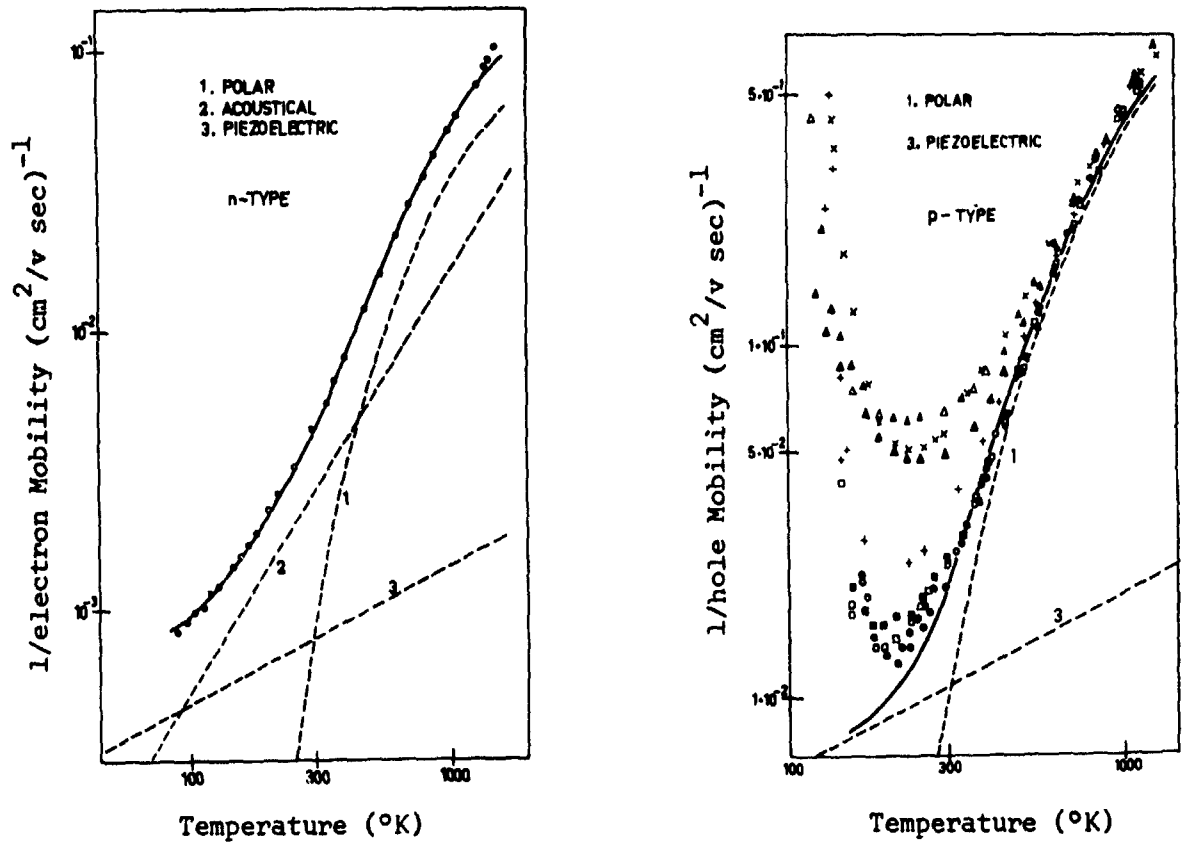
Mobility as a function of temperature for n-type, single crystal, alpha-silicon carbide, prepared in argon, or argon + nitrogen.

a - no dopant $n_n = 3.6 \times 10^{17}$/cc
b - N-, Al-, B-, n $\sim 10^{17}$
c - N-, Al-, B-, n $\sim 10^{18}$
d - N-, Al-, B-, n $= 3 \times 10^{18}$
e - N-, Al-, B-, n $= 10^{19}$
f - N-doped, n $= 5 \times 10^{19}$
g - N-doped n $= 3.4 \times 10^{19}$

[Ref. 3608]

SILICON CARBIDE

MOBILITY



Mobility as a function of temperature for p-type, single crystal, alpha-silicon carbide, (6H). Principal dopants are aluminum, boron, and chlorine. Nitrogen is always present. Dashed lines are calculated for - 1) polar, 2) acoustical, and 3) piezoelectric scattering. The solid line is the sum of the two and the dots show experimental points.

- ● argon grown (fairly pure)
- + × { oxygen, oxygen and chlorine
- △ ▲ { aluminum
- □ ■ { boron
- ○ chlorine-doped

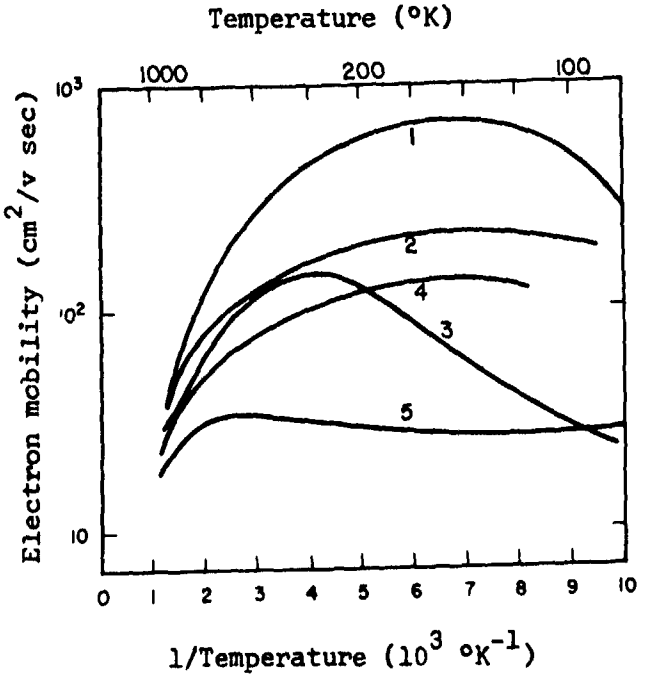
[Ref. 8783]

SILICON CARBIDE

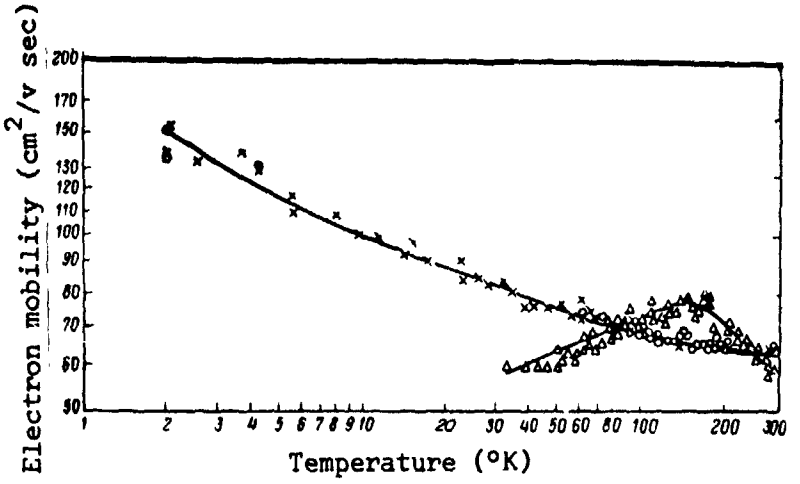
MOBILITY

Mobility as a function of temperature for n-type, N-doped, single crystal, alpha-silicon carbide.

	ρ_{300K} ohm-cm	n /cc
1 -	0.425	10^{17}
2 -	0.2	10^{17}
3 -	0.53	3×10^{18}
4 -	0.48	4×10^{18}
5 -	0.0085	2×10^{19}



[Ref. 16397]



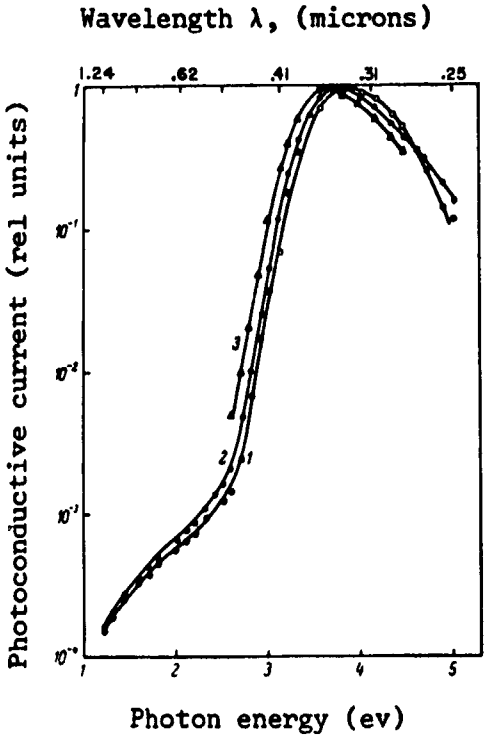
Electron mobility as a function of temperature for n-type, single crystal, alpha-silicon carbide, (111) oriented.

	n /cc	ρ_{290K} ohm-cm
1) o	5.7×10^{18}	.0175
2) x		.0174
3) ▽	5.6×10^{17}	.222

[Ref. 17973]

SILICON CARBIDE

PHOTOELECTRONIC PROPERTIES



[Ref. 4596]

Photoconductivity as a function of wavelength for n-type, single crystal, alpha-silicon carbide, (6H), (001) oriented.

ρ_{300K} = 7.5 ohm-cm.

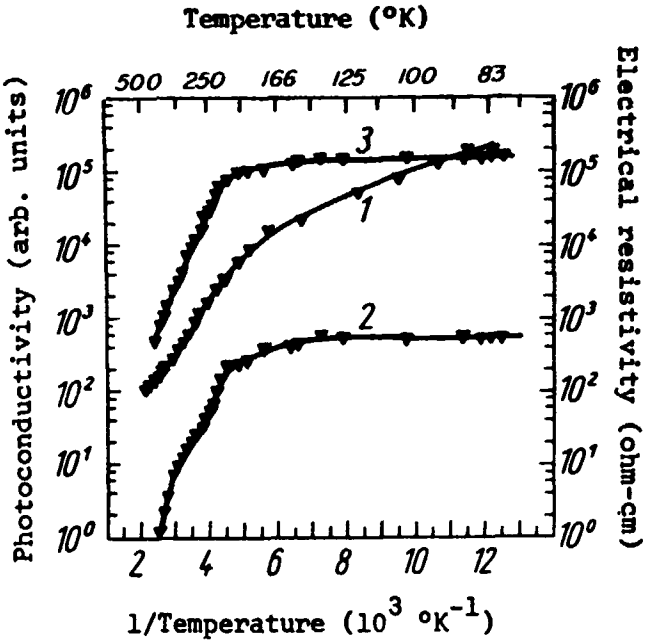
1 - 100°K
2 - 293°K
3 - 500°K

SILICON CARBIDE

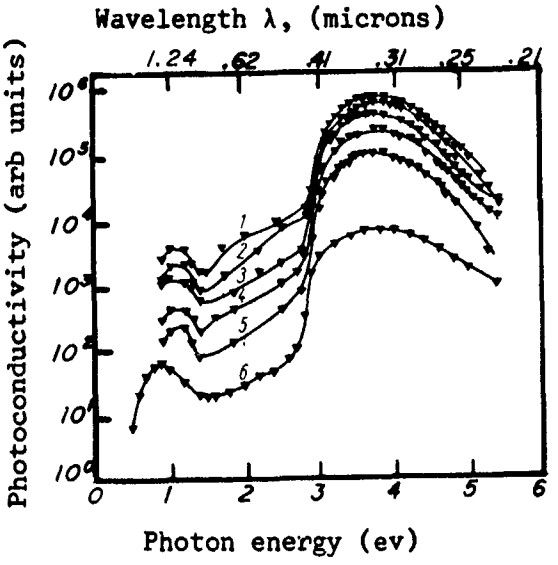
PHOTOELECTRONIC PROPERTIES

Photoconductivity and electrical resistivity as a function of temperature for n-type, single crystal, alpha-silicon carbide.

1 - electrical resistivity
2 - photoconductivity at 1.03 microns
3 - photoconductivity at 0.32 microns



[Ref. 10994]



Photoconductivity as a function of wavelength for n-type, single crystal, alpha-silicon carbide.

1 - 125°K
2 - 180°K
3 - 200°K
4 - 230°K
5 - 260°K
6 - 300°K

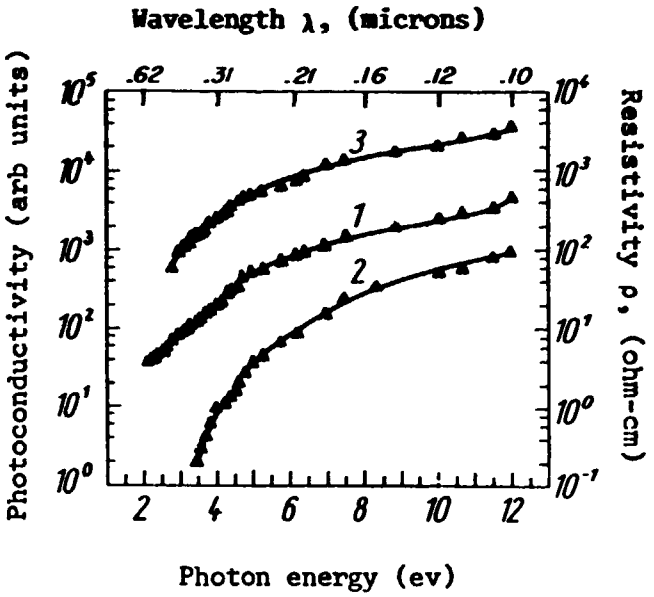
[Ref. 10994]

SILICON CARBIDE

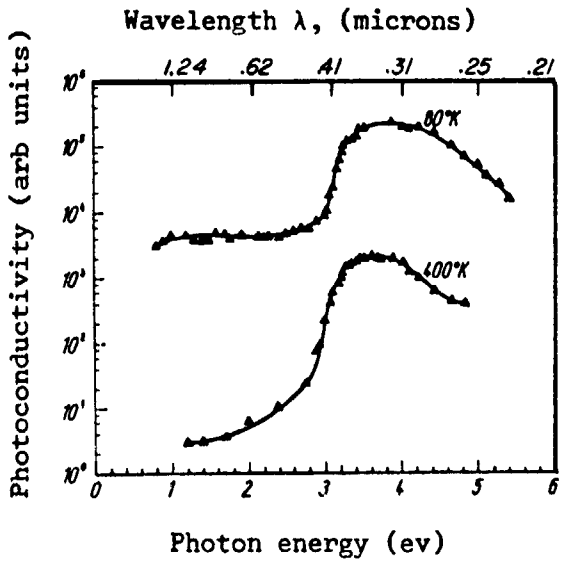
PHOTOELECTRONIC PROPERTIES

Photoconductivity and electrical resistivity as a function of temperature for p-type, single crystal, alpha-silicon carbide.

1 - electrical resistivity
2 - photoconductivity at 1.05 microns
3 - photoconductivity at 0.35 microns



[Ref. 10994]



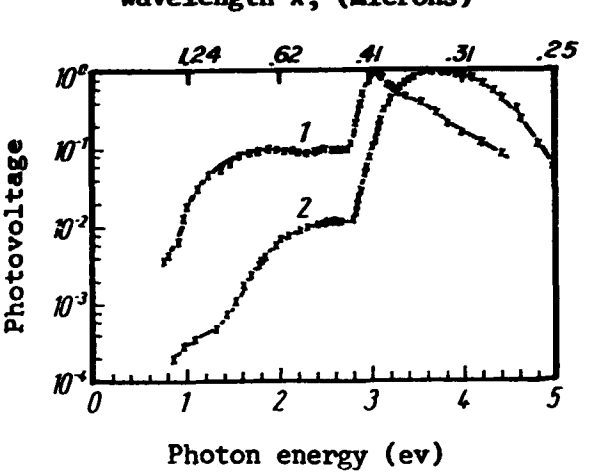
Photoconductivity as a function of wavelength for p-type, single crystal, alpha-silicon carbide at 80°K and 400°K.

[Ref. 10994]

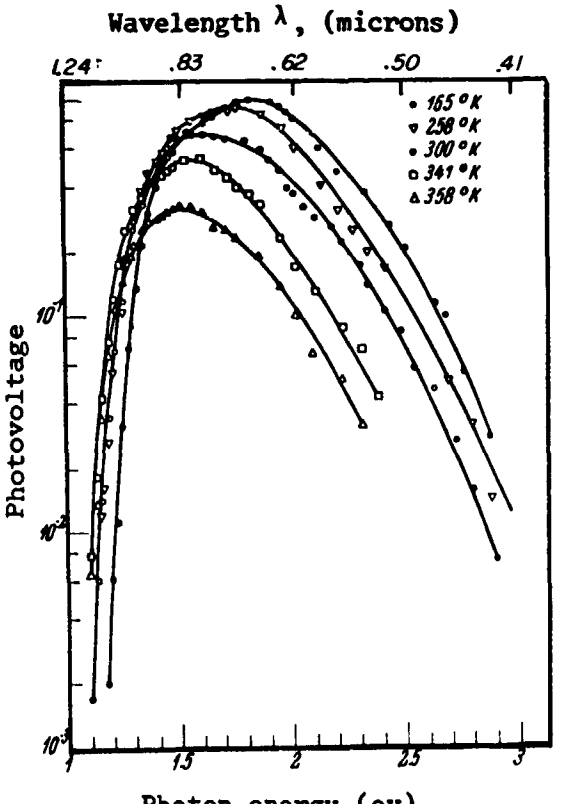
SILICON CARBIDE

PHOTOELECTRONIC PROPERTIES

Photoconductivity (1) and photovoltage (2) for n-type, single crystal, alpha-silicon carbide at 300°K. Photovoltage normalized to 1. Photoconductivity placed only for comparison, without units.



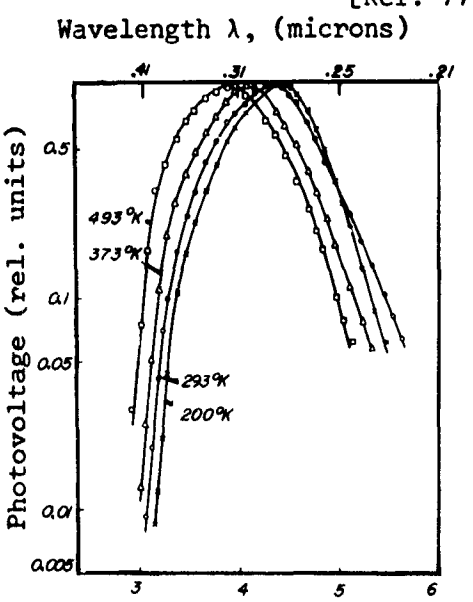
[Ref. 10994]



Photovoltage as a function of wavelength for p-type, single crystal, alpha-silicon carbide at several temperatures. Photovoltage normalized to 1.

[Ref. 7741]

Photovoltage as a function of wavelength for p-n junction, single crystal alpha-silicon carbide at various temperatures.

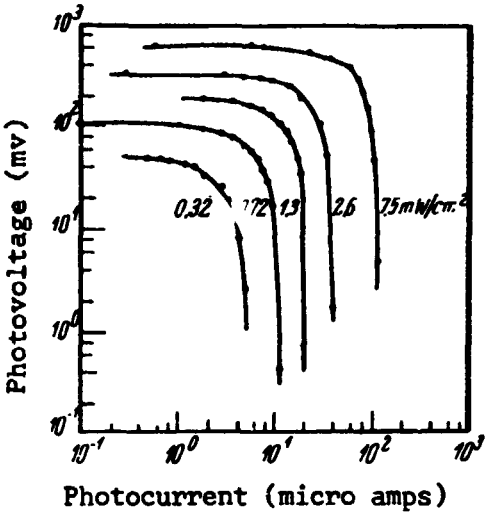


[Ref. 7867]

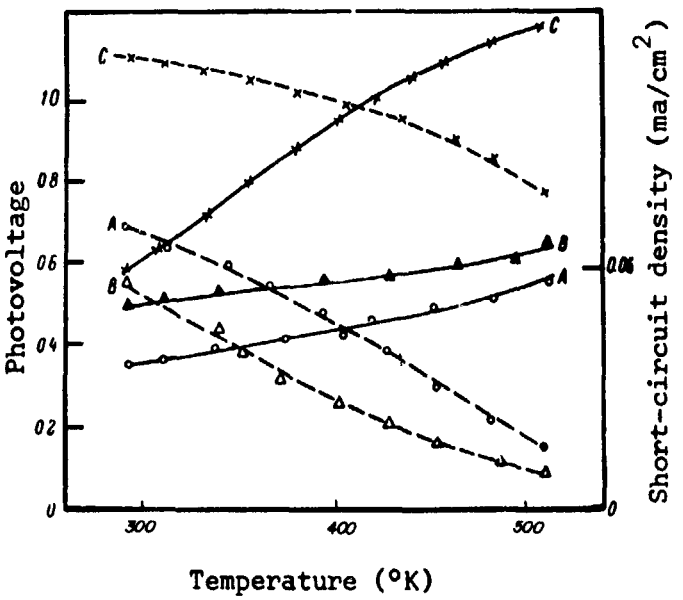
SILICON CARBIDE

PHOTOELECTRONIC PROPERTIES

Current-Voltage curve of an n-type, single crystal, alpha-silicon carbide photoelement at light intensities from .32 to 7.5 mW/cm^2.



[Ref. 7741]



Photovoltage and short circuit current density as a function of temperature for p-n junction, single crystal, alpha-silicon carbide at constant illumination.

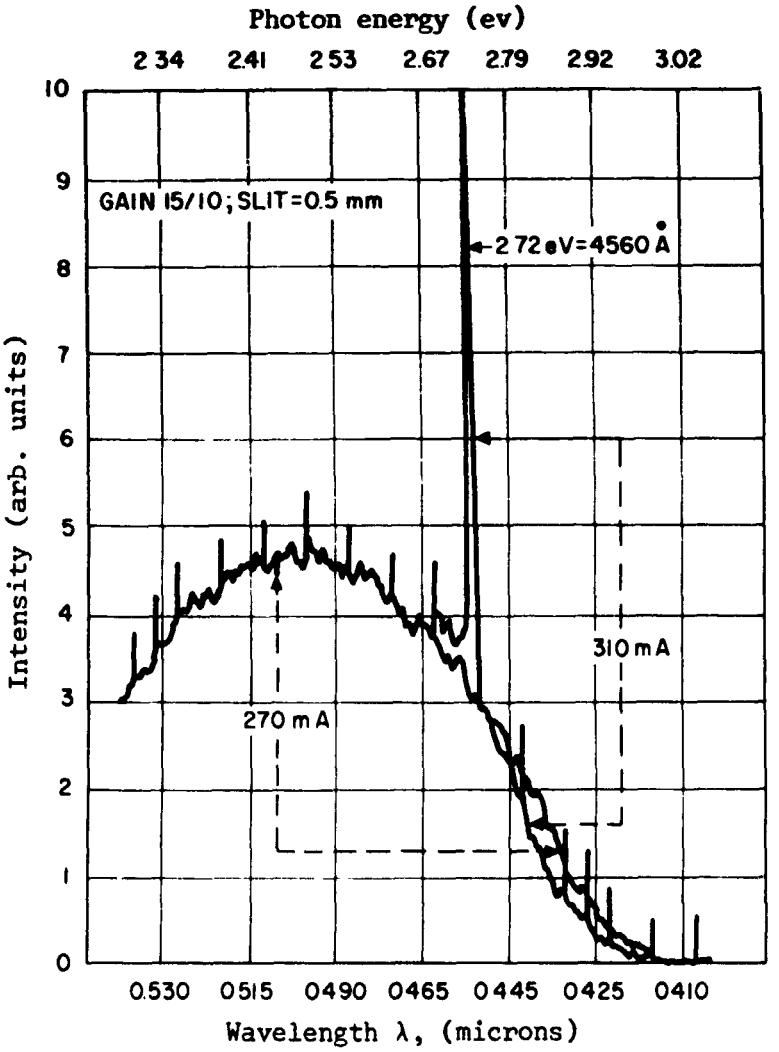
— short circuit density

--- photovoltage

[Ref. 7867]

SILICON CARBIDE

PHOTON ELECTROLUMINESCENCE



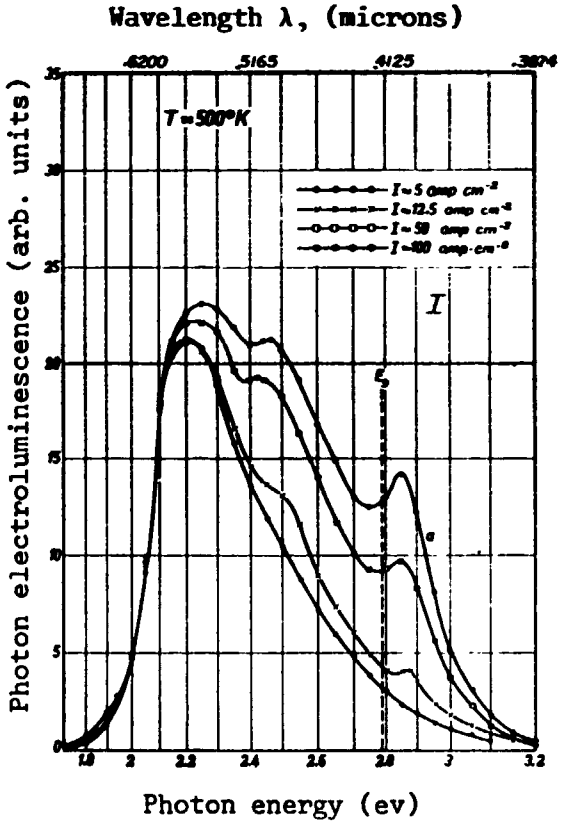
Stimulated emission in a forward-biased p-n junction of alpha-silicon carbide. Emission peak at .456 microns has a linewidth <0.005 microns. Continuous operation at 300°K around 120 amps/cm^2.

[Ref. 17972]

SILICON CARBIDE

PHOTON ELECTROLUMINESCENCE

Photo electroluminescence as a function of wavelength for single crystal, alpha-silicon carbide p-n junction at 500°K, and several current intensities.



a is the same curve on both graphs on a different scale.

[Ref. 18406]

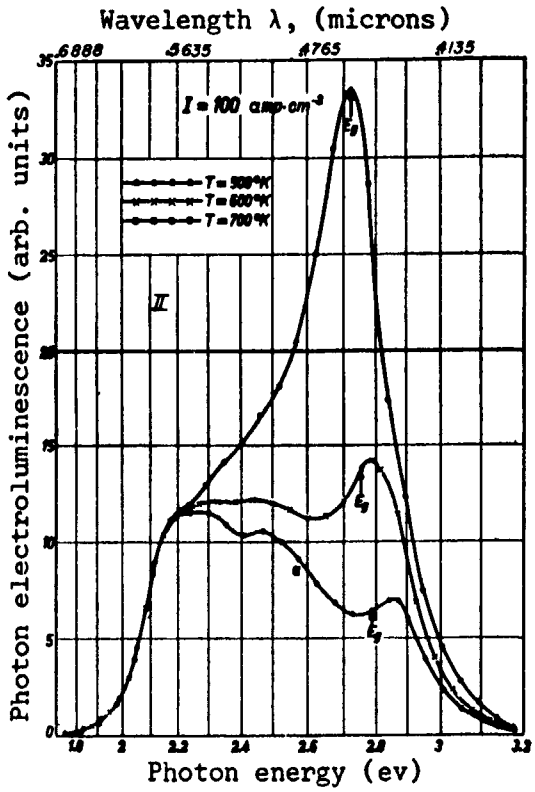


Photo electroluminescence as a function of wavelength for single crystal, alpha-silicon carbide p-n junction at several temperatures and 100 amps/cm^2.

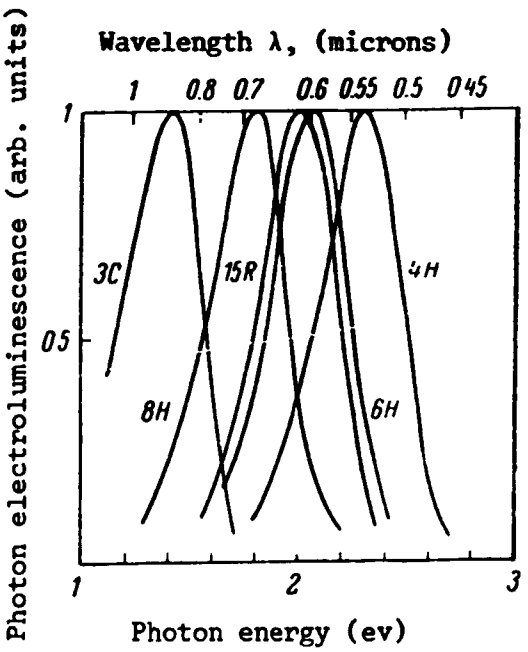
[Ref. 18406]

SILICON CARBIDE

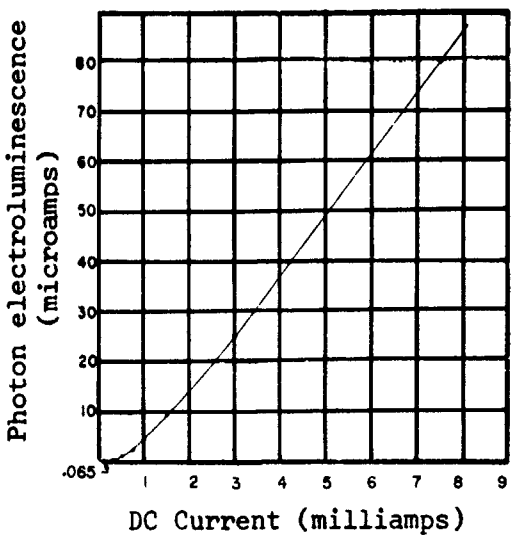
PHOTON ELECTROLUMINESCENCE

Electroluminescence as a function of wavelength in single crystal, alpha-silicon carbide p-n junctions of several polytypes at 300°K. $\rho < .3$ ohm-cm. The 3C curve is for n-type, beta-silicon carbide, $\rho < 0.4$ ohm-cm. Current density was 0.05 to 0.1 amp/cm^2.

Photon electroluminescence is measured in photons/unit time and energy.



[Ref. 18818]



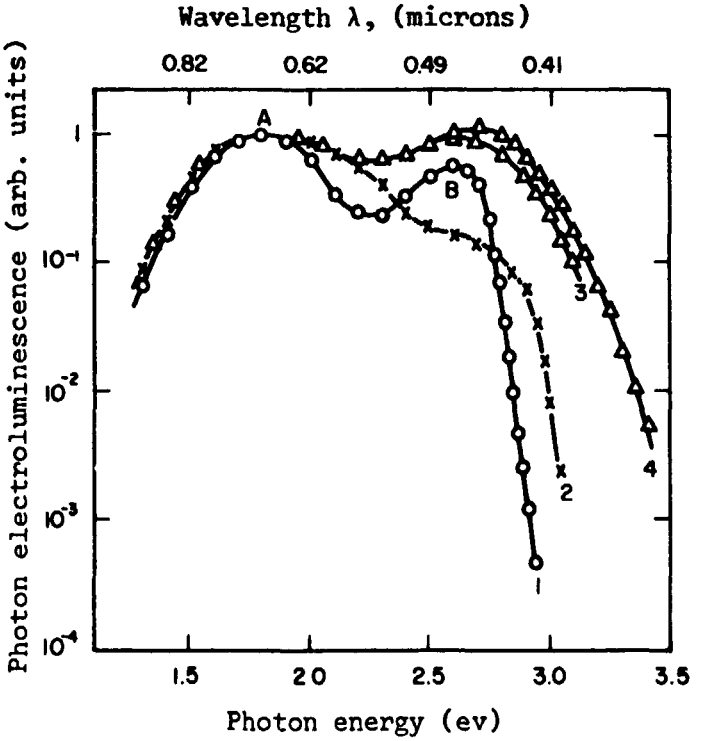
Electroluminescence as a function of DC current in fairly pure, light green, single crystal, alpha-silicon carbide p-n junction at 300°K.

The curve starts at .065 milliamp.

[Ref. 2152]

SILICON CARBIDE

PHOTON ELECTROLUMINESCENCE



Photon electroluminescence in single crystal, alpha-silicon carbide p-n junction. Various impurities are present.

$n \sim 10^{18}$/cc., ρ = .2 ohm-cm.

1 - 130°K, 1 amp/cm^2
2 - 400°K, 1 amp/cm^2
3 - 700°K, 1 amp/cm^2
4 - 700°K, 100 amps/cm^2

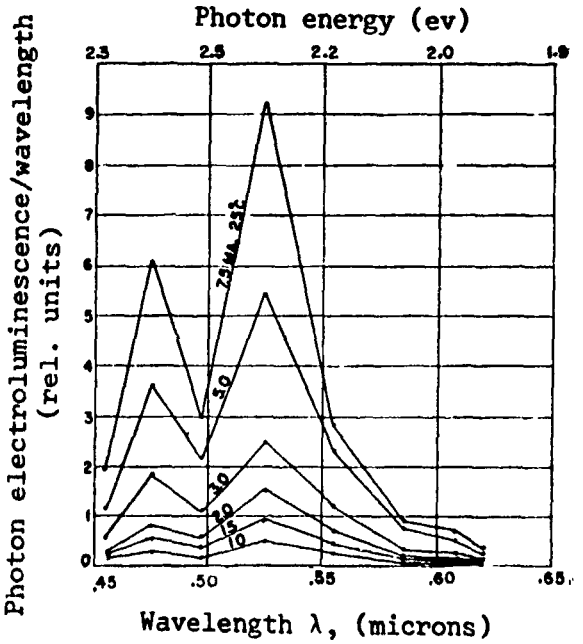
[Ref. 17457]

Photon electroluminescence is measured in photons/unit time and energy.

SILICON CARBIDE

PHOTON ELECTROLUMINESCENCE

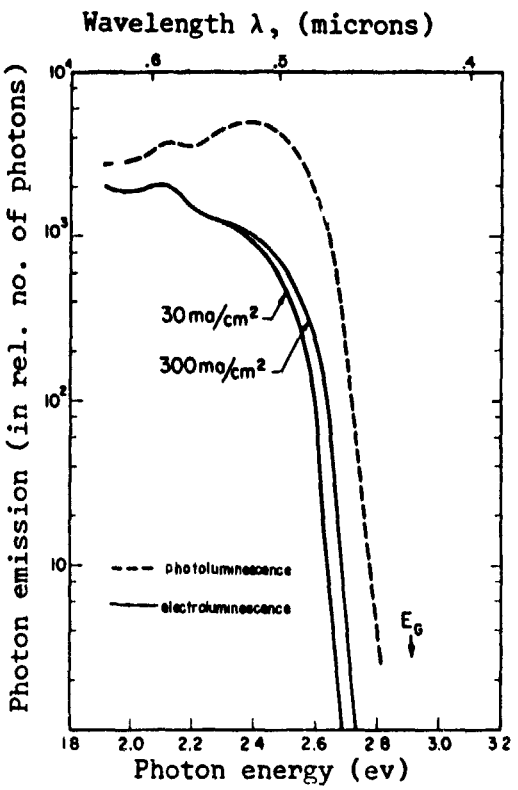
Normalized photon electroluminescence as a function of wavelength in n-type, single crystal, pale green, alpha-silicon carbide at 300°K. The current varies from 1.0 to 7.5 microamps.



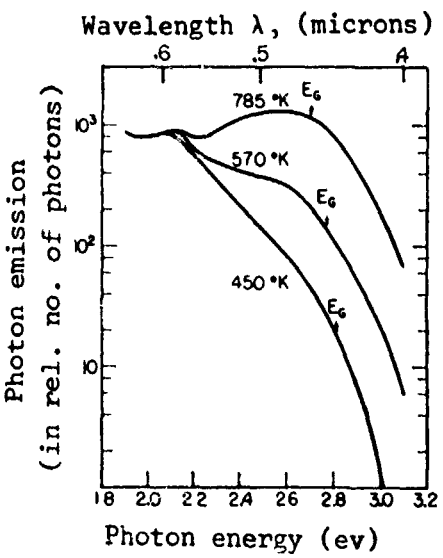
[Ref. 2152]

Photon and electroluminescence as a function of wavelength for single crystal, alpha-silicon carbide p-n junction at 77°K. Increase in excitation by a factor of 10 is indicated in electroluminescent spectra by shift to higher wavelength, but similar increase in UV excitation has no effect on photoluminescent spectrum.

[Ref. 368]



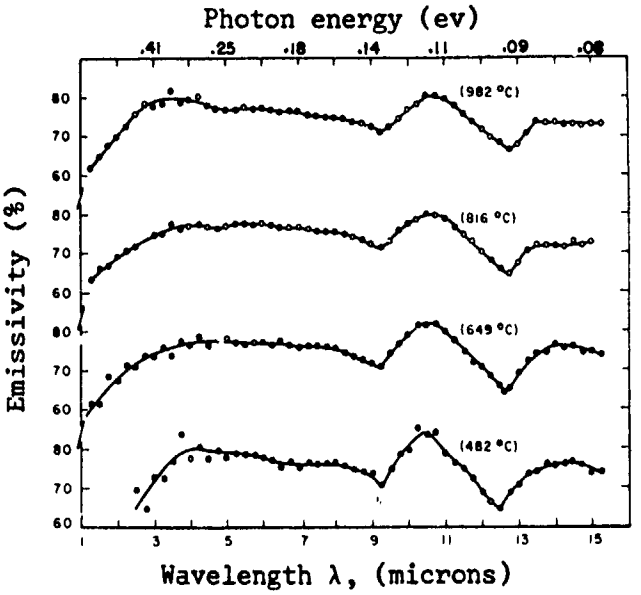
Electroluminescence as a function of wavelength for single crystal, alpha-silicon carbide p-n junction, at several temperatures and 1 amp/cm^2. Curves are normalized at .6 microns.



[Ref. 368]

SILICON CARBIDE

PHOTON EMISSIVITY



[Ref. 2217]

Spectral emissivity of Globar heating element as a function of wavelength at four temperatures.

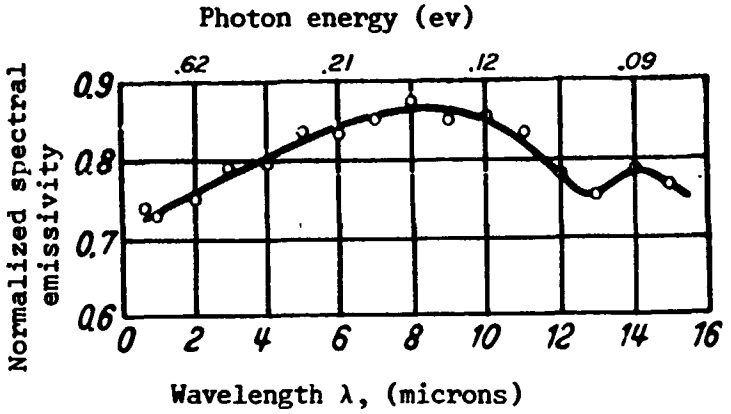
Spectral Emissivity

Value	Sample	Temperature	Ref.
0.85%	sintered silicon carbide rods at 1.6 microns	1243°K	17724
0.93%	polycrystalline commercial silicon carbide	1500°F	1956

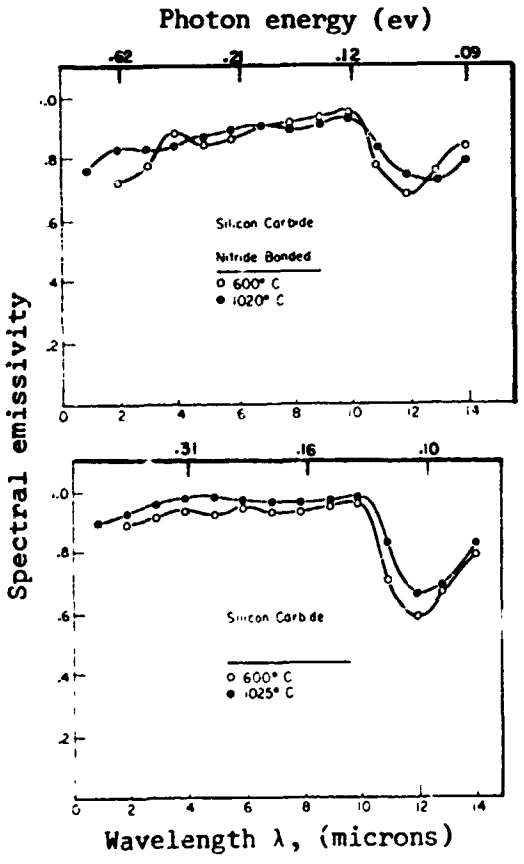
SILICON CARBIDE

PHOTON EMISSIVITY

Spectral emissivity as a function of wavelength for sintered silicon carbide rods at 1243°K. Spectral emissivity is normalized to the standard black body base.



[Ref. 17724]



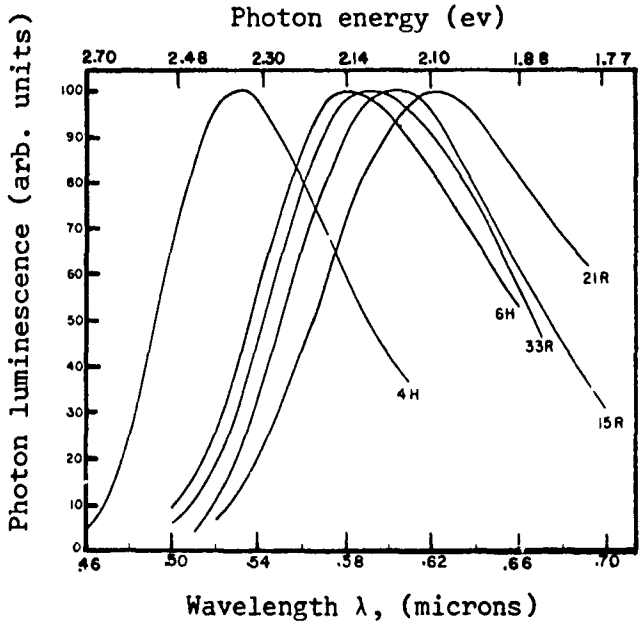
Spectral emissivity as a function of wavelength for commercially pure, fine grained silicon carbide at 2 temperatures.

[Ref. 17412]

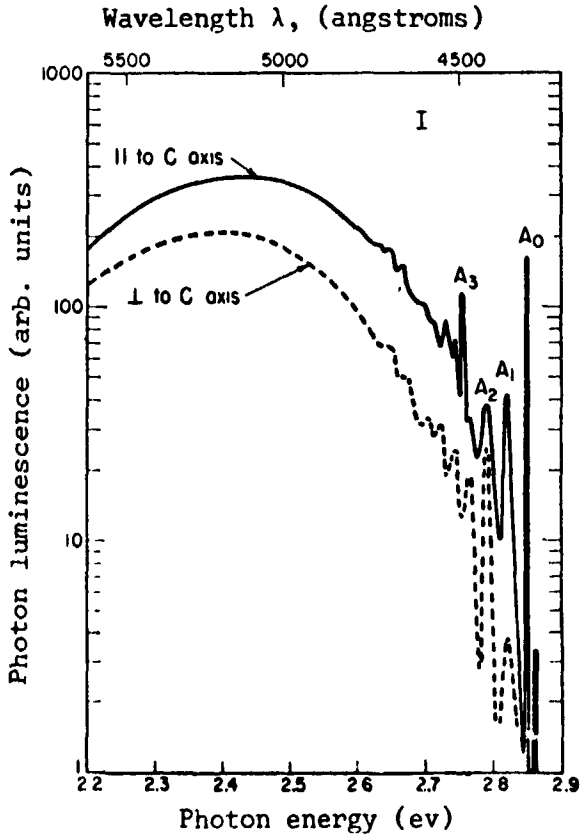
SILICON CARBIDE

PHOTON LUMINESCENCE

Photon luminescence as a function of wavelength for alpha-silicon carbide powder, B-, and N-doped, at 300°K. Curves indicate the polytype from x-ray determinations.



[Ref. 17404]

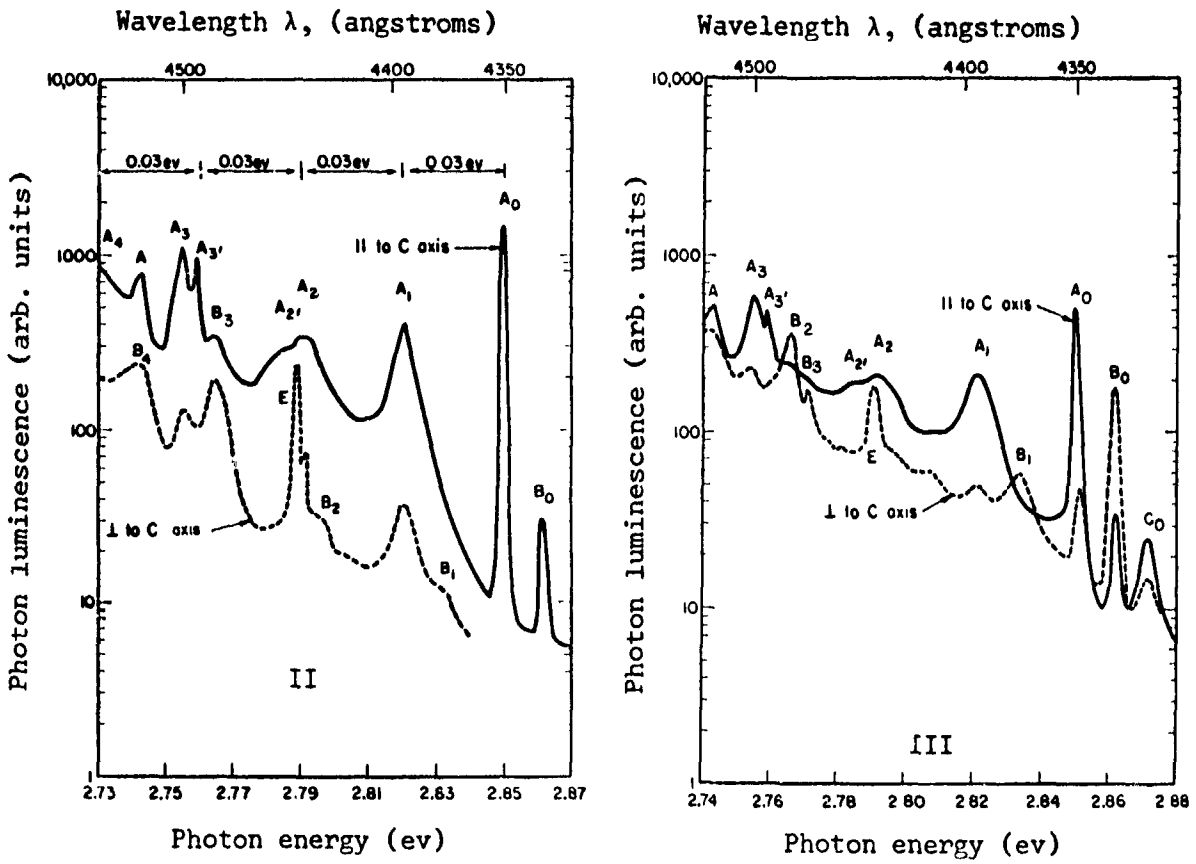


Photon luminescence as a function of wavelength for single crystal, alpha-silicon carbide, (6H), at 4°K, (001) oriented. The subscripts indicate the level number.

[Ref. 11690]

SILICON CARBIDE

PHOTON LUMINESCENCE



[Ref. 11690]

Photon luminescence for single crystal, alpha-silicon carbide, (6H), at 4°K and 77°K, giving fine structure of the peaks in I.

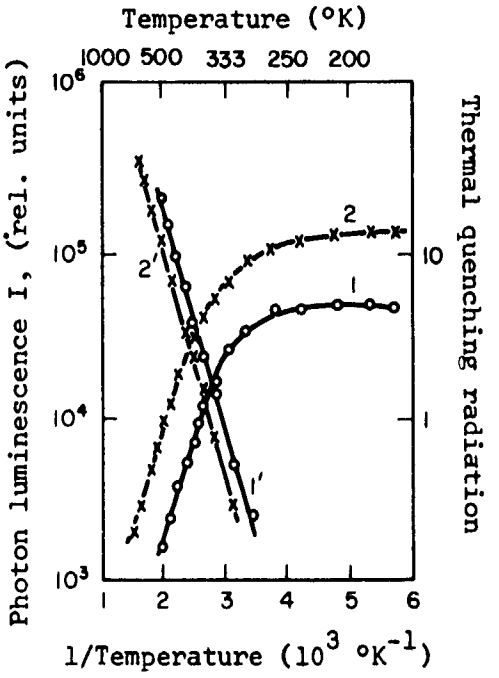
SILICON CARBIDE

PHOTON LUMINESCENCE

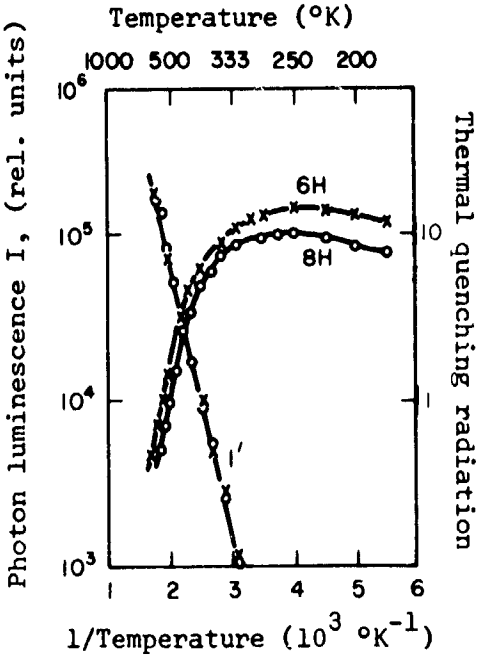
Photon luminescence as a function of temperature for single crystal, beta-silicon carbide p-n junction, (nitrogen-boron). ρ = 0.08-0.4 ohm-cm.

1, 2 - photoluminescence for UV irradiation

1′ , 2′, - quenching curves whose slope equal thermal quenching activation energy 0.29-0.3 ev.



[Ref. 18818]



Photon luminescence as a function of temperature for single crystal, alpha-silicon carbide (6H) and (8H) p-n junction, (nitrogen-boron). ρ = 0.05 to 0.3 ohm-cm.

1′ is quenching curve whose slope is ∿ 0.35 ev.

[Ref. 18818]

SILICON CARBIDE

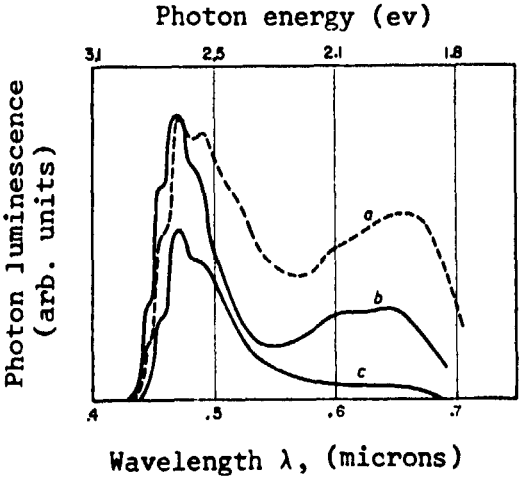
PHOTON LUMINESCENCE

Photon luminescence as a function of wavelength for single crystal, alpha-silicon carbide at 63°K.

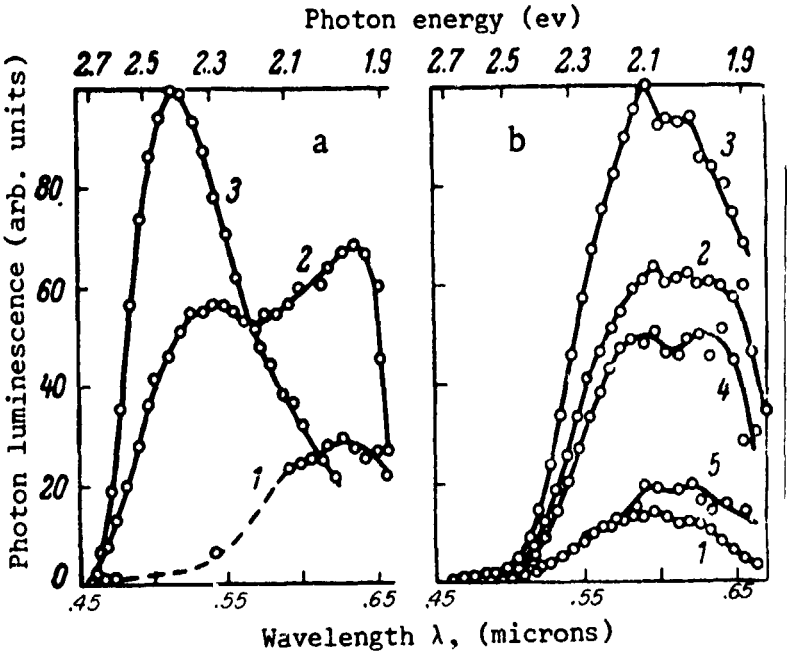
a - n-type, N-doped, white, n ∿ 10^{18}/cc

b - n-type, N-doped, green, n = 2.7 x 10^{18}

c - p-type, Al-doped, light blue, n ∿ 10^{18}



[Ref. 3607]



Photon luminescence as a function of wavelength for single crystal, alpha-silicon carbide, (6H), at several temperatures.

a) transparent colorless crystal,

1 - 423°K
2 - 123°K
3 - 90°K

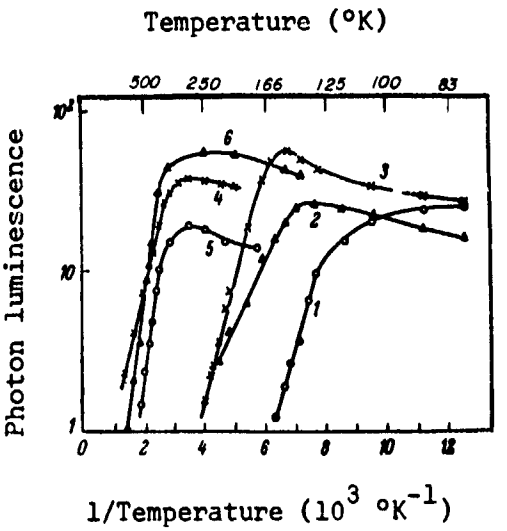
b) black crystal,

1 - 423°K
2 - 333°K
3 - 273°K
4 - 194°K
5 - 90°K

[Ref. 13404]

SILICON CARBIDE

PHOTON LUMINESCENCE



curves 1, 2, 3

Photon luminescence as a function of temperature for n-type, single crystal, alpha-silicon carbide, (6H), nitrogen-doped.

$n = 10^{17}$ to 5×10^{18}/cc, ρ_{300K} = 0.02 to 1 ohm-cm.

curves 4, 5, 6

Photon luminescence as a function of temperature for single crystal, alpha-silicon carbide p-n junctions.

Curves 4 and 5 are for the (6H) polytype
Curve 6 is for the (4H) polytype.

[Ref. 17730]

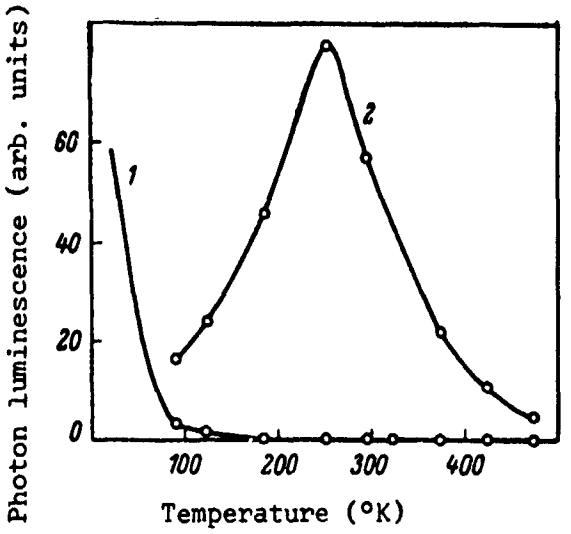
SILICON CARBIDE

PHOTON LUMINESCENCE

Photon luminescence as a function of temperature for n-type, single crystal, alpha-silicon carbide, (6H).

1 - blue luminescence

2 - orange



[Ref. 13404]

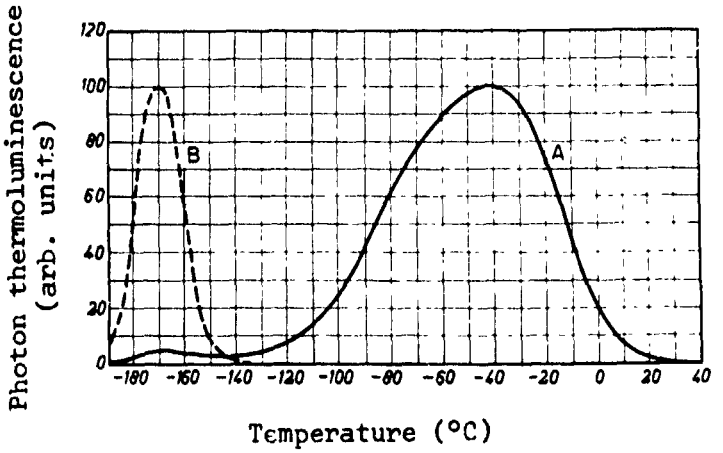
Photoluminescence maxima, dopant, and electrical resistivity for single crystal, beta-silicon carbide.

Crystal Type	Dopant	Resistivity (ohm-cm)	Luminescence at 77°K Color	Luminescence at 300°K Color
n	Al	10^3	brilliant orange	yellow
p-n	Al		brilliant pink	none
p	Al	10	brilliant pink	none
n	$+N_2$ + Al	10^{-1}	bright orange	dull red
n	Al, Mo + N_2	10^{-2}	bright pink	yellow
n	Al, + N_2	10^{-1}	orange	dull red
n	Mg	1 - 10	pink	none
n		1 - 10	orange	green, yellow, red
n		4 - 10	dull orange	yellow, red, green
p	Al	10^{-1}	very dull green, pink, yellow	none
n	Ca	1 - 10	very dull red	dull red
n	B	10^3	very dull orange	bright yellow, red & green

[Ref. 17725]

SILICON CARBIDE

PHOTON THERMOLUMINESCENCE



Photon thermoluminescence as a function of temperature for single crystal, alpha-silicon carbide. Excitation at 83°K and .365 microns.

A - p-type, Al-doped, light blue, $n \sim 10^{18}$/cc.

B - n-type, nitrogen-doped, white, $n \sim 10^{18}$/cc.

[Ref. 3607]

SILICON CARBIDE

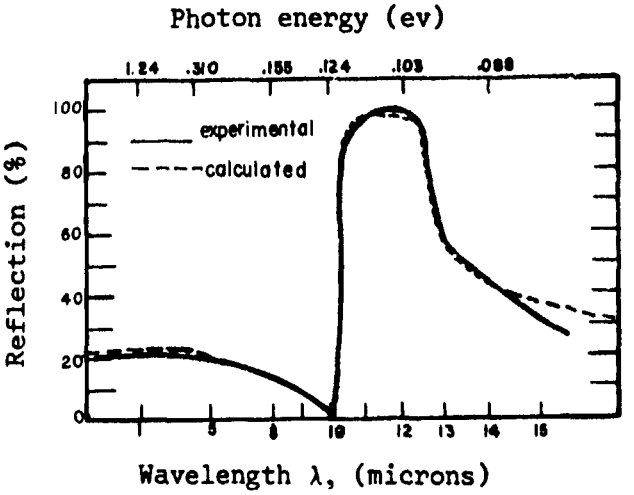
REFLECTIVITY

Reflectivity as a function of wavelength for pure, single crystal, alpha-silicon carbide at 300°K.

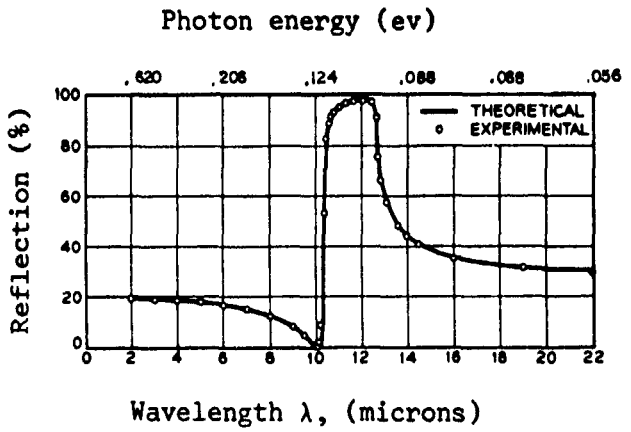
$E \parallel$ to the c-axis

$n_{\varepsilon} \perp$ to the c-axis

$n_{\omega} \parallel$ to the c-axis

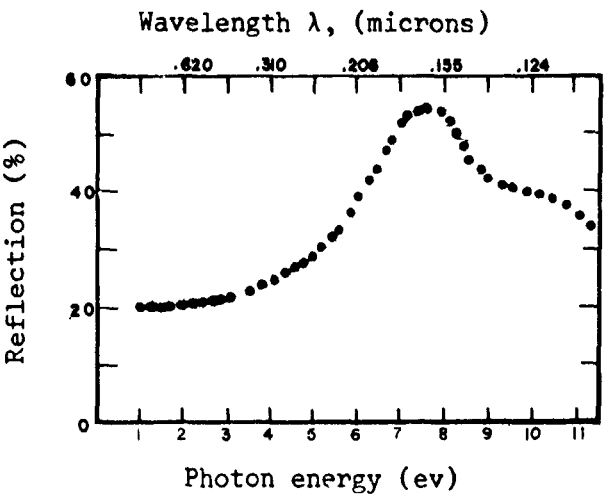


[Ref. 3607]



Resistivity as a function of wavelength for single crystal, alpha-silicon carbide, (6H), at 300°K. E is parallel to the c-axis.

[Ref. 628]



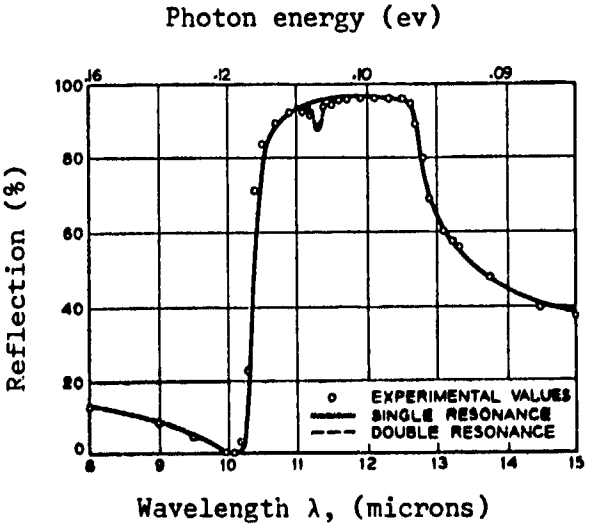
Reflectivity as a function of wavelength for single crystal, alpha-silicon carbide at 300°K. Below 3 ev these values are calculated from direct measurements of index of refraction in [Ref. 13873].

[Ref. 17419]

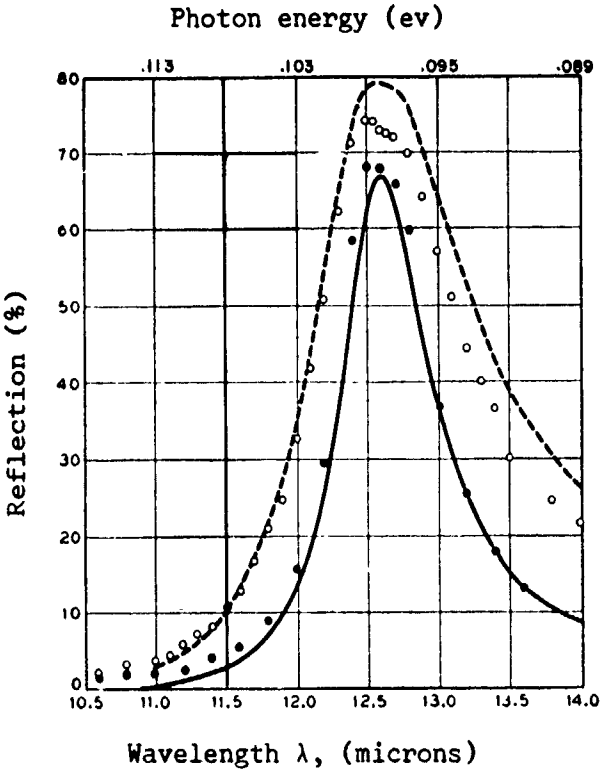
SILICON CARBIDE

REFLECTIVITY

Reflectivity as a function of wavelength for single crystal, alpha-silicon carbide, (6H), at 300°K. E is normal to the c-axis.



[Ref. 628]



Reflectivity as a function of wavelength for polycrystalline, beta-silicon carbide films at 300°K.

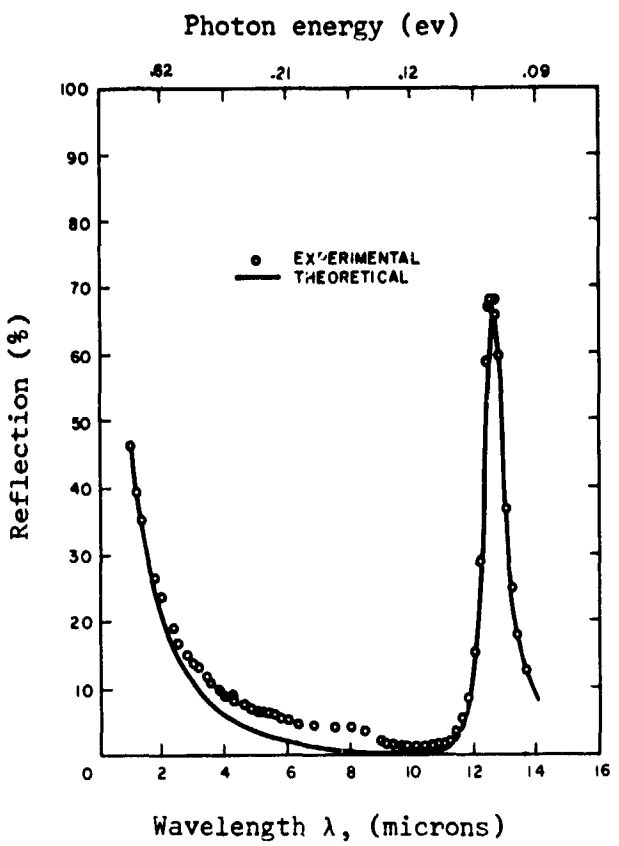
• - 0.06 microns thick

○ - 0.12 microns thick

[Ref. 627]

SILICON CARBIDE

REFLECTIVITY



[Ref. 627]

Reflectivity as a function of wavelength for polycrystalline, beta-silicon carbide film, 0.06 microns thick.

SILICON CARBIDE

REFRACTIVE INDEX

Symbol	Value (at 300°K)		Sample (single crystal)	Test Method (wavelength)	Ref.
n	∿ 2.63		β-, yellow to olive green	.6708μ	13873
	ε	ω			
	2.673	2.633	α-, (001), green-black	.6708μ	*Larsen
	2.697	2.654	(Moissanite)	.5895μ	
	2.721	2.675		.5351μ	
	2.6889	2.6475	α-, (6H), light green	.5895μ	13873
	2.6892	2.6468	α-, (15R), pale green	.5895μ	13873
	2.654	2.616	α-, pale green	.755μ	**Gmelin

.6708μ is Li
.5895μ is Na
.5351μ is Tl

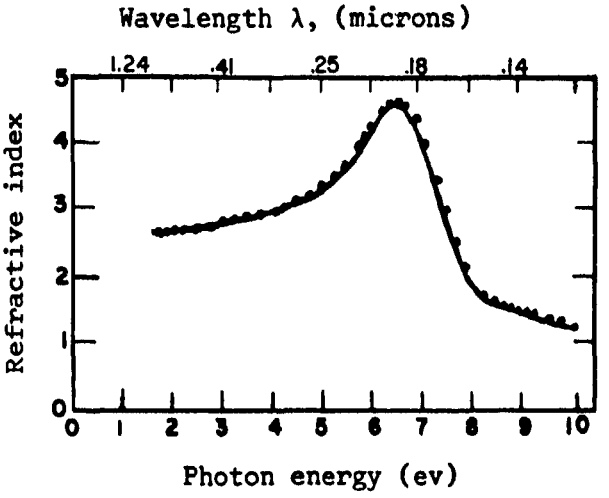
* Larsen, E.S., and H. Berman. The Microscopic Determination of the Nonopaque Minerals. U.S.G.P.O., Washington, 1934. p. 77

** GMELINS HANDBUCH DER ANORGANISCHEN CHEMIE; achte völlig neu bearbeitete Auflage. Silicium. Teil B. Weinheim, Verlag Chemie, GMBH, 1959. p. 827.

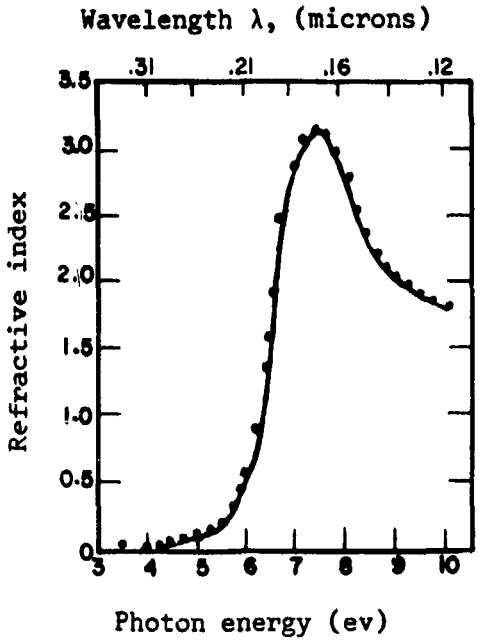
SILICON CARBIDE

REFRACTIVE INDEX

Index of refraction of single crystal, alpha-silicon carbide, (6H), at 300°K. Below 3 ev the values are taken from [Ref. 13873].



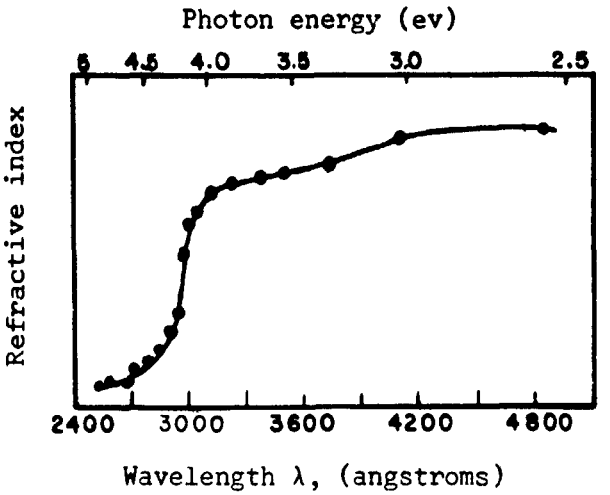
[Ref. 17419]



The extinction coefficient, i.e., the imaginary part of the index of refraction, of single crystal, alpha-silicon carbide, (6H), at 300°K.

[Ref. 17419]

Refractive index as a function of wavelength for pure, single crystal, alpha-silicon carbide at 300°K. (Calculated from reflectivity data.)

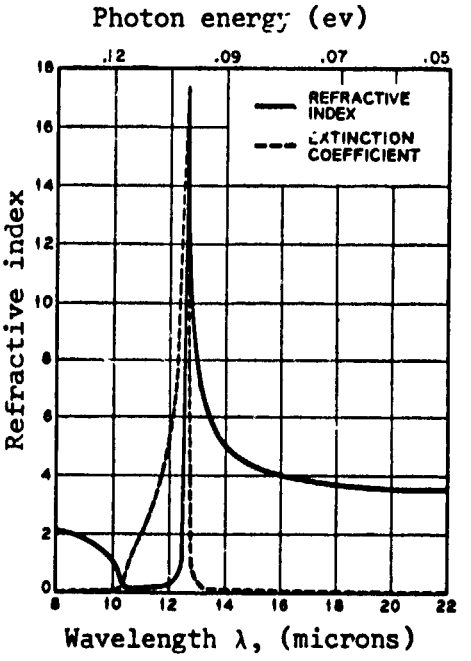


[Ref. 13404]

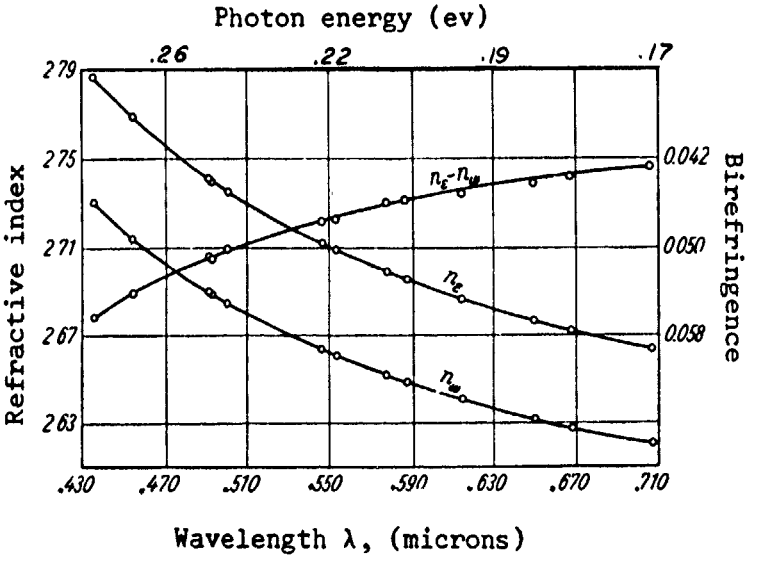
SILICON CARBIDE

REFRACTIVE INDEX

The theoretically calculated optical constants as a function of wavelength for single crystal, n-type, alpha-silicon carbide, (6H).



[Ref. 628]



Refractive index of ordinary n_ε rays and extraordinary n_ω rays as a function of wavelength in fairly pure, single crystal, alpha-silicon carbide at 300°K. $n_\varepsilon - n_\omega$ is the birefringence curve.*

*Gmelin, p. 827

SILICON CARBIDE

THERMAL CONDUCTIVITY

Thermal conductivity as a function of temperature for single crystal, alpha-silicon carbide of varied purity.

A - n-type, N-doped, colorless, (6H),

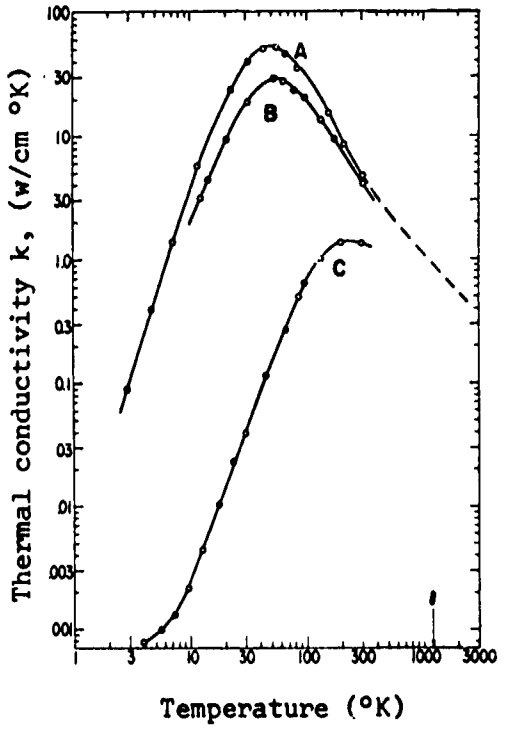
$n \sim 10^{17}$/cc., $\rho_{300K} \sim$ 10 ohm-cm.

B - n-type, N- & Al-doped, light green, (6H),

$n \sim 10^{19}$/cc., ρ_{300K} = 2 ohm-cm.

C - p-type, Al-doped, dark blue, (6H & 15R),

$n = 4 \times 10^{19}$/cc., $\rho_{300K} \sim$ .6 ohm-cm.



[Ref. 17406]

Thermal conductivity of sample A. Slightly N-doped.

Temperature °K	Thermal Conductivity w/cm deg.	Ref.
50	52	17406
70	43	
100	28	
150	15	
200	9.5	
300	4.9	
500	2.4*	
1000	1.1*	
1200	0.9*	17406
1478	.157**	1956
343	2.05***	17374

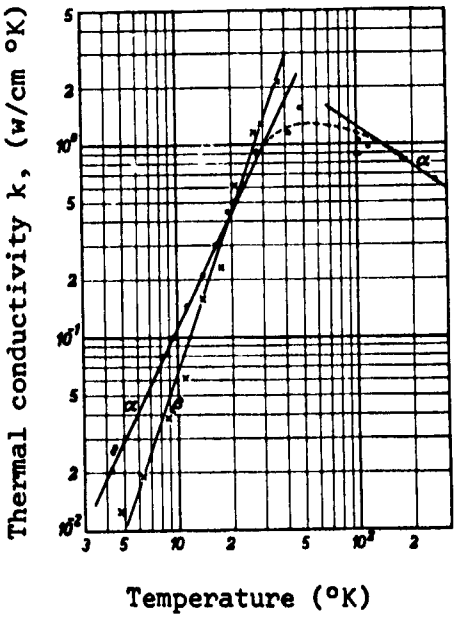
* extrapolated
** commercial polycrystalline, alpha-silicon carbide
*** polycrystalline

SILICON CARBIDE

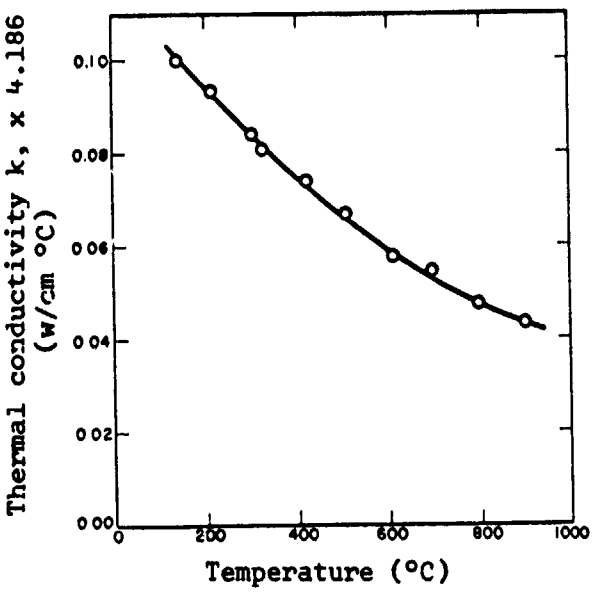
THERMAL CONDUCTIVITY

Thermal conductivity as a function of temperature for single crystal, alpha-silicon carbide, (6H), and N-doped, polycrystalline, beta-silicon carbide.

$n < 10^{17}/cc.$



[Ref. 19150]



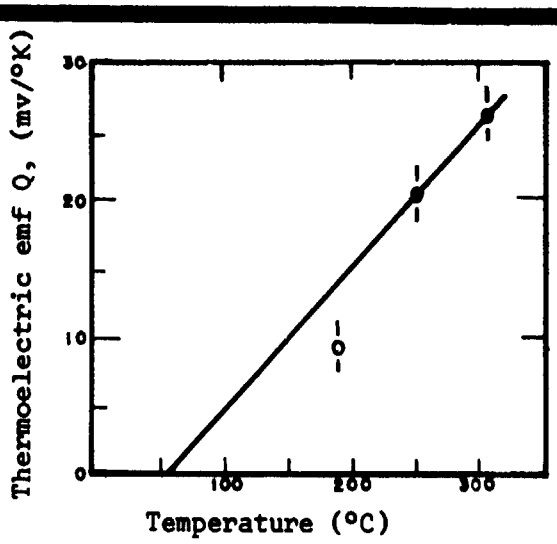
Thermal conductivity as a function of temperature for commercial, polycrystalline, alpha-silicon carbide.

[Ref. 17411]

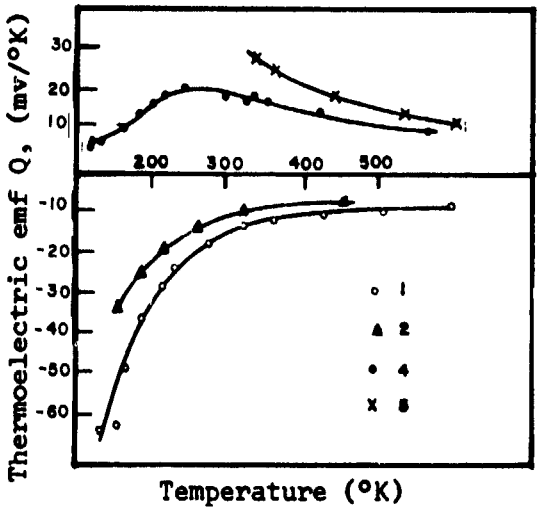
SILICON CARBIDE

THERMOELECTRIC PROPERTIES

Thermoelectric emf as a function of temperature for n-type, single crystal, yellow, beta-silicon carbide.
$\rho \sim 1$ to 100 ohm-cm.



[Ref. 17416]



Thermoelectric emf as a function of temperature for single crystal, alpha-silicon carbide with resistivities to 10^4 ohm-cm.

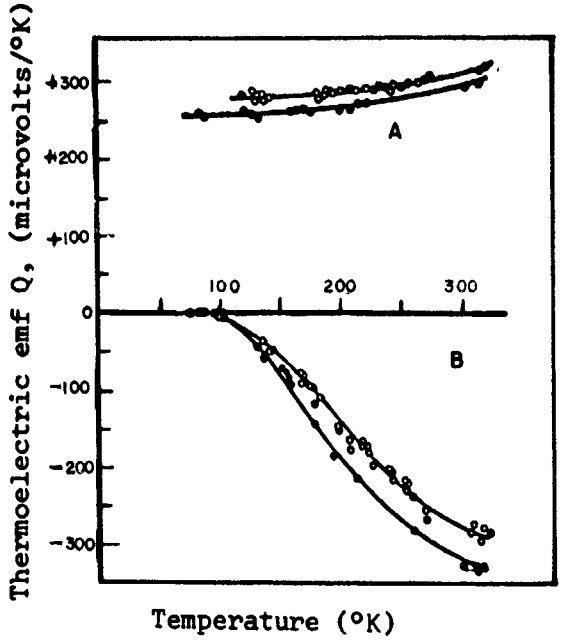
1 - n-type, $n = 5.6 \times 10^{16}$/cc
2 - n-type, $n = 2.7 \times 10^{17}$
4 - n-type, $n = 2.7 \times 10^{17}$
5 - p-type, $n = 2.0 \times 10^{18}$

[Ref. 5896]

Thermal emf as a function of temperature for single crystal, alpha-silicon carbide.

A - n-type, N-doped, green

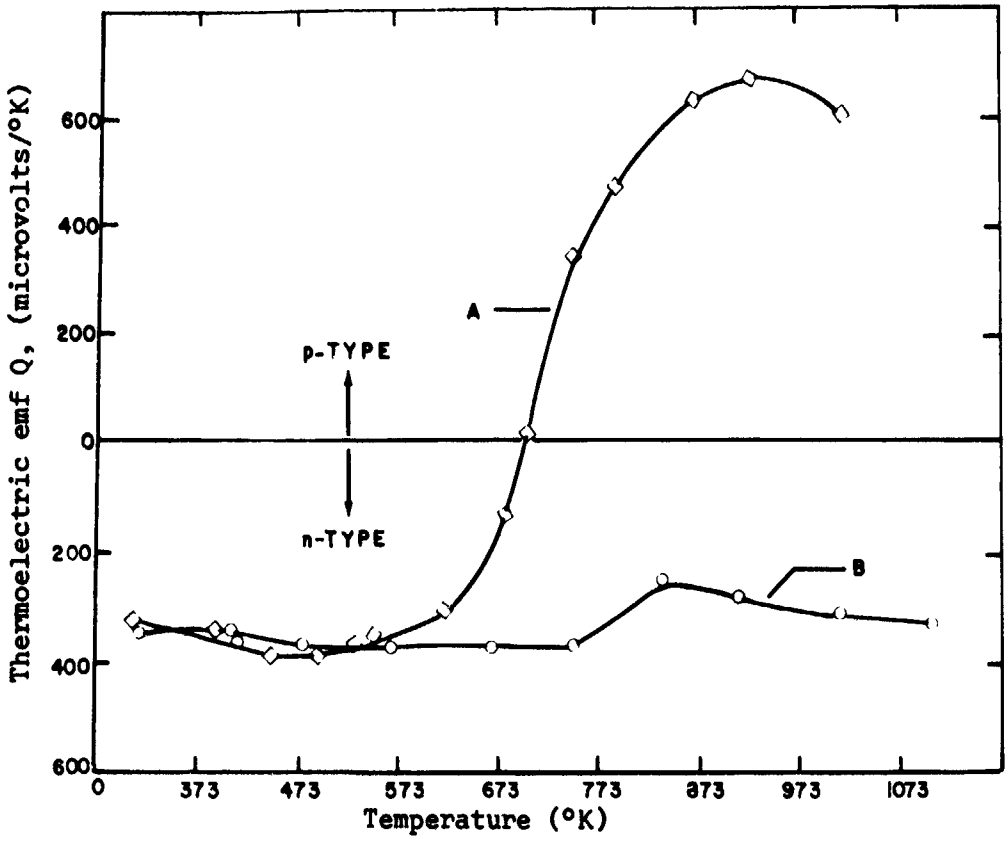
B - p-type, Al-doped, black



[Ref. 6031]

SILICON CARBIDE

THERMOELECTRIC PROPERTIES



Thermoelectric emf as a function of temperature for two silicon carbide samples.

A - Single crystal, alpha-silicon carbide, ρ = 45 ohm-cm, colorless, becomes p-type above 680°K.

B - Single crystal, n-type, alpha-silicon carbide, ρ = 0.026 ohm-cm, dark green, remains n-type with heating.

[Ref. 19560]

Symbol	Value (μv/°K)	Sample	Ref.
Q	20-50	polycrystalline commercial material, ρ ∿ 0.05 ohm-cm	3974
	200 ± 10%	polycrystalline, β-SiC rods	17416
	-106	n-type, single crystal, yellow, β-, ρ = 0.1 to 100 ohm-cm	17416

SILICON CARBIDE

WORK FUNCTION

Symbol	Value (ev)	Sample (single crystal)	Test Method	Temperature	Ref.
ϕ	4.62	impure, p-type, α-, ρ = 0.3 ohm-cm., black	photoelectric emission	300°K	7134
ϕ	4.55	impure, p-type, α-, ρ = 0.6 ohm-cm., green	"		7134
ϕ	~ 4	impure, α-,	electron thermionic emission	1000-1700°K	7152
	~3 ev (2.3 to 4)	impure, n- and p-type, black green to light green yellow		300-800°K	2468
Electron affinity ψ ~4 ev		β-	photoelectric data	300°K	787
Photoelectric threshold ~7 ev		β-	"	"	787

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